IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Perspective

Hitoshi Murayama (IPMU Tokyo & Berkeley)

US-Japan Collaboration in HEP

The 30th anniversary symposium

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

30 years

- 1978 ICHEP@Tokyo
  - Standard Model “established”
- 1984 *W*/*Z* discovery
- 1989-2001 SLC/LEP precision measurements
- 1995 top quark discovery
- 2002 CP violation in B
- we kept verifying the Standard Model

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- *the only missing particle is Higgs boson*
- *So aren't we done once Higgs found?*

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BERKELEY CENTER FOR THEORETICAL PHYSICS

T-shirt ready

$$
\begin{aligned}
\mathcal{L} = & \\
& -\frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\
& + \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i \\
& + (Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i e_j H + c.c.) \\
& - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}
\end{aligned}
$$

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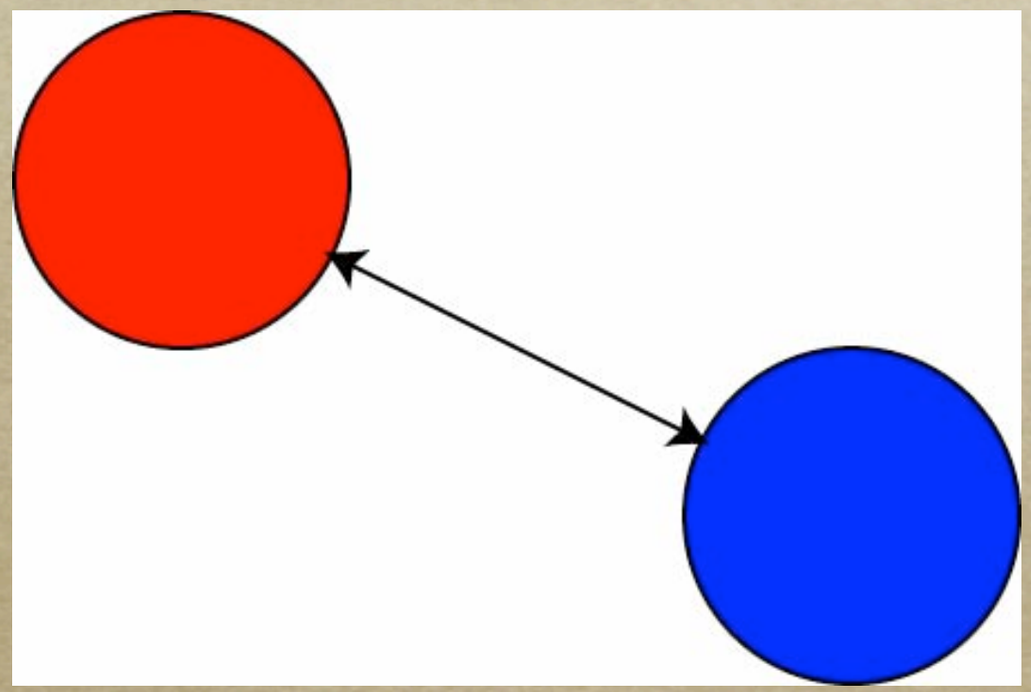
  - *We'll start with Higgs boson(s)*

Mystery of the weak force

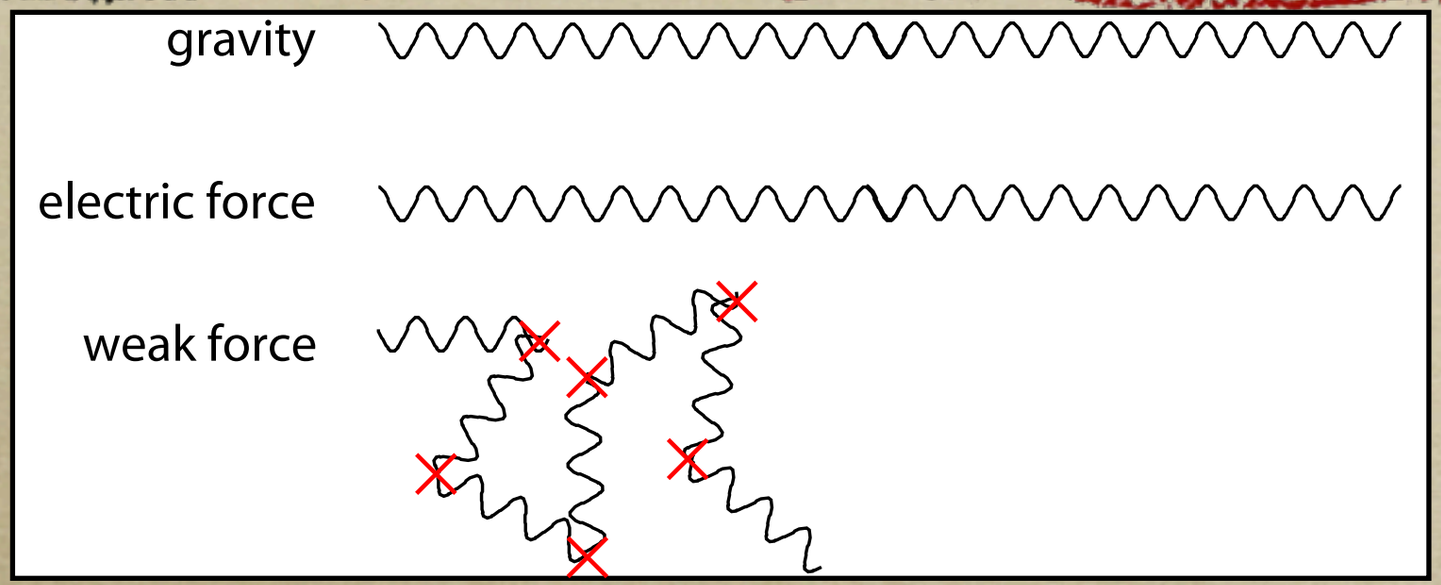
- *Gravity pulls two massive bodies (long-ranged)*



- *Electric force repels two like charges (long-ranged)*

- *"Weak force" pulls protons and electrons (short-ranged) acts only over* a billionth nanometer

Something is in the Universe



- *There is a quantum liquid filling our Universe*
- *It doesn't disturb gravity or electric force*
- *It does disturb weak force and make it short-ranged*
- *It also slows down all elementary particles from speed of light*
- *What is it?? "Dark Field"*

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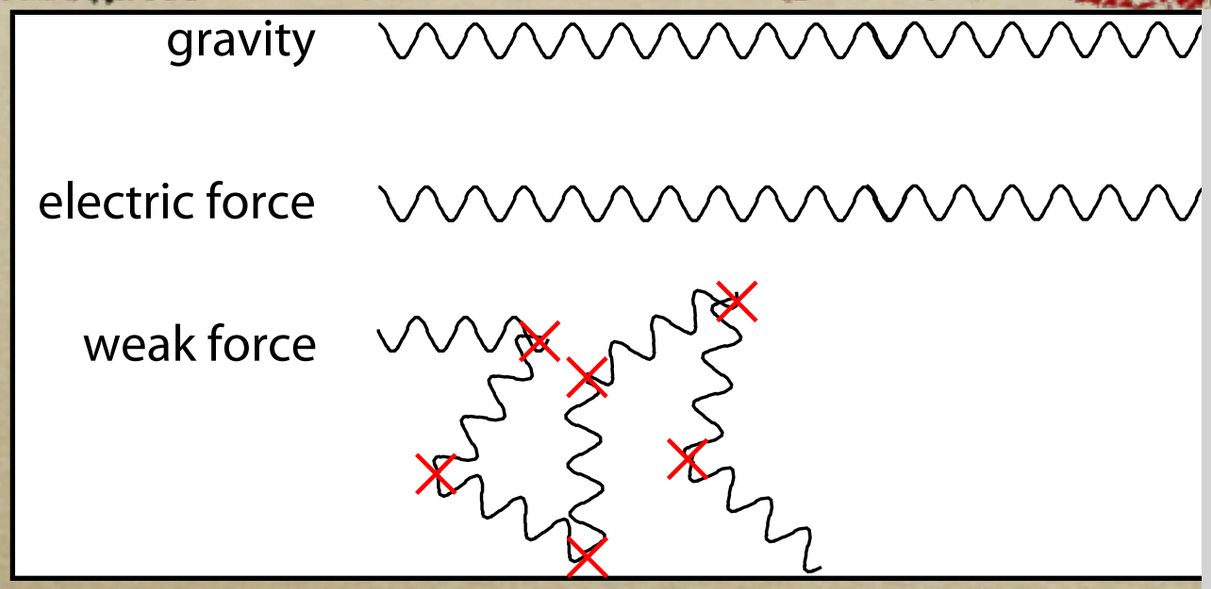

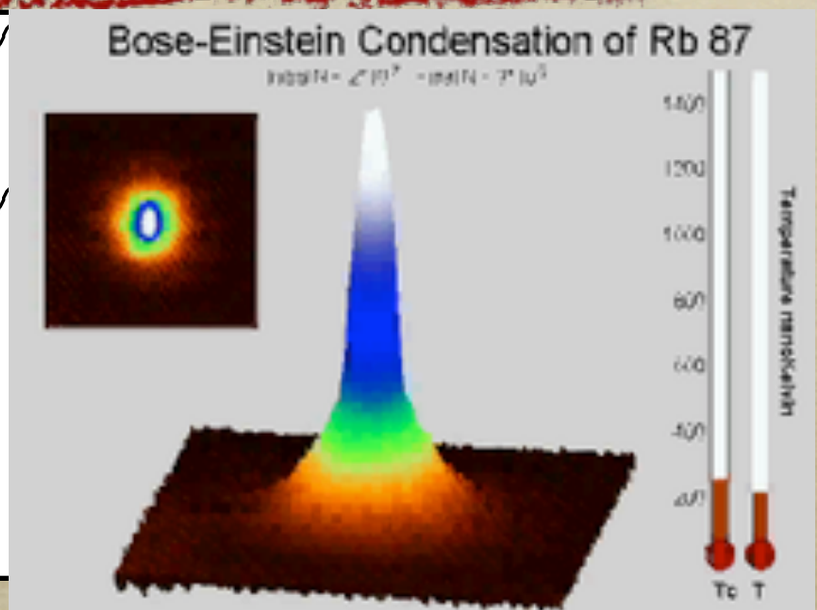

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Like a superconductor

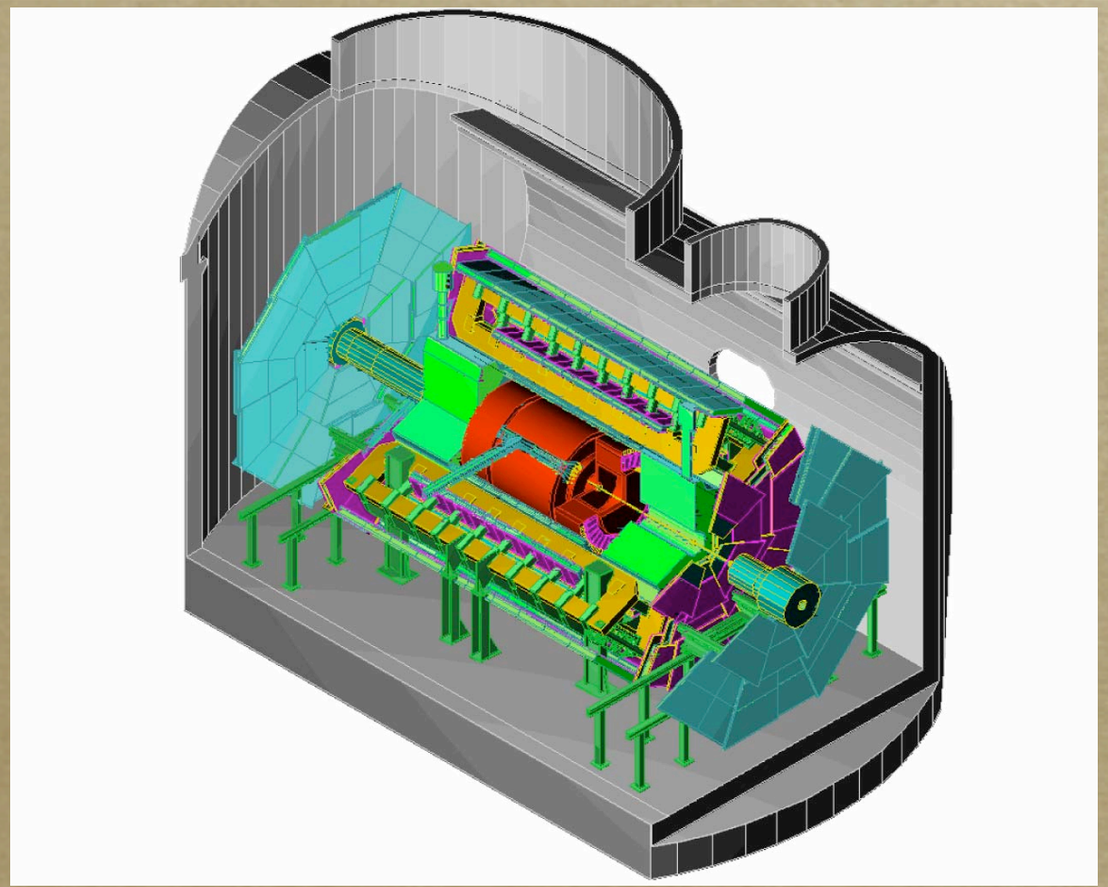
- *In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"*

  ⇒ *Magnetic field is short-ranged!*

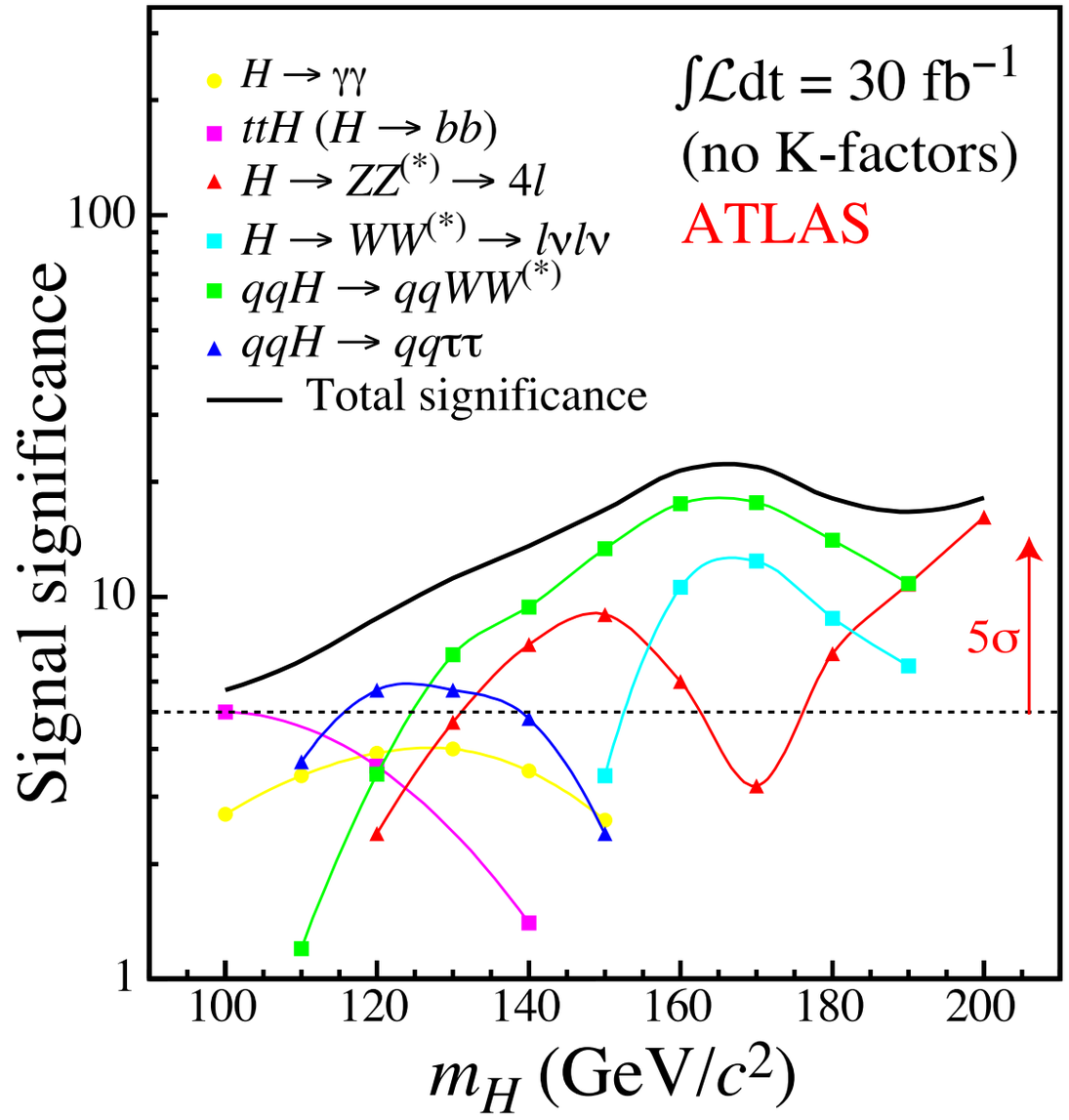
- *Imagine a physicist living in a superconductor*
- *She finally figured:*
  - *magnetic field must be long-ranged*
  - *there must be a mysterious charge-two condensate in her "Universe"*
  - *But doesn't know what the condensate is, nor why it condenses*
  - *Doesn't have enough energy (gap) to break up Cooper pairs*

That's the stage where we are!

Standard Model Higgs at LHC

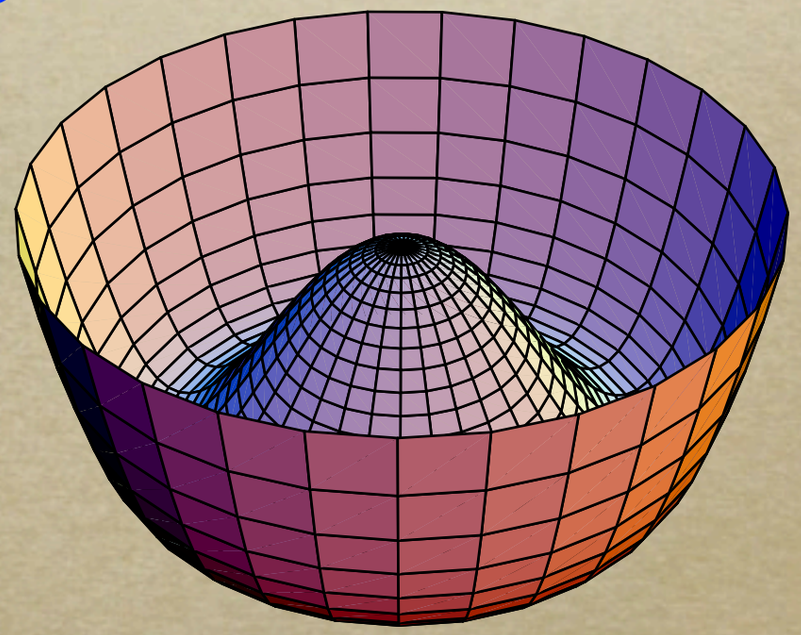


Robust discovery



Post-Higgs Problem

- *We see "what" makes up the Dark Field*
- *But we still don't know "why" it is there*
- *Two problems:*
  - *Why anything is condensed at all*
  - *Why is the scale of condensation* $\sim$TeV$\ll M_{Pl}=10^{15}$TeV



- *Explanation most likely to be at ~TeV scale because this is the relevant energy scale, cf. BCS*

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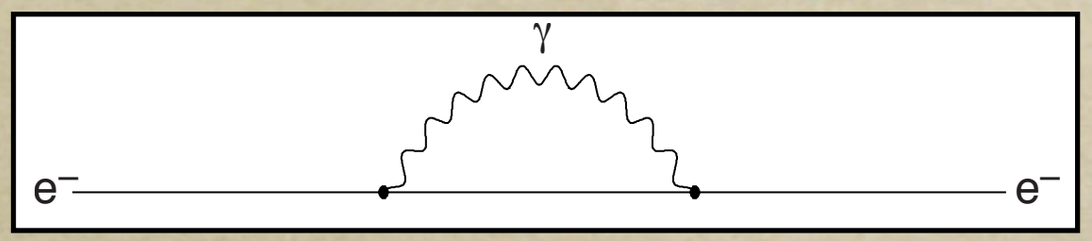
$\Rightarrow$ *Can't discuss physics below* 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- *Electron creates a force to repel itself*
- *Vacuum bubble of matter anti-matter creation/annihilation*
- *Electron annihilates the positron in the bubble*

⇒ *only 10% of mass even for Planck-size electron*



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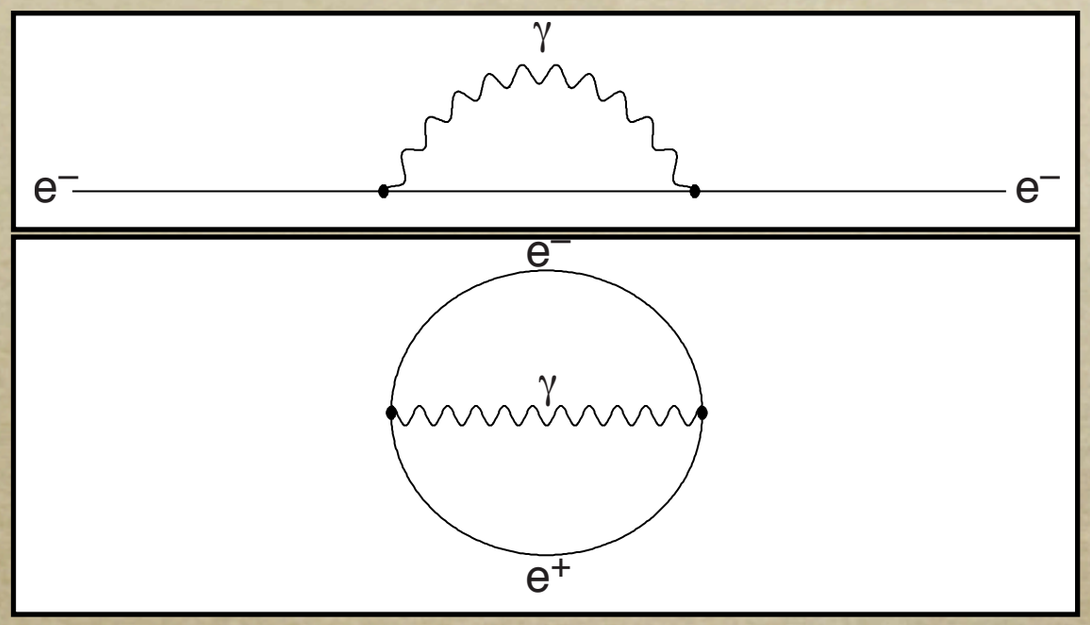

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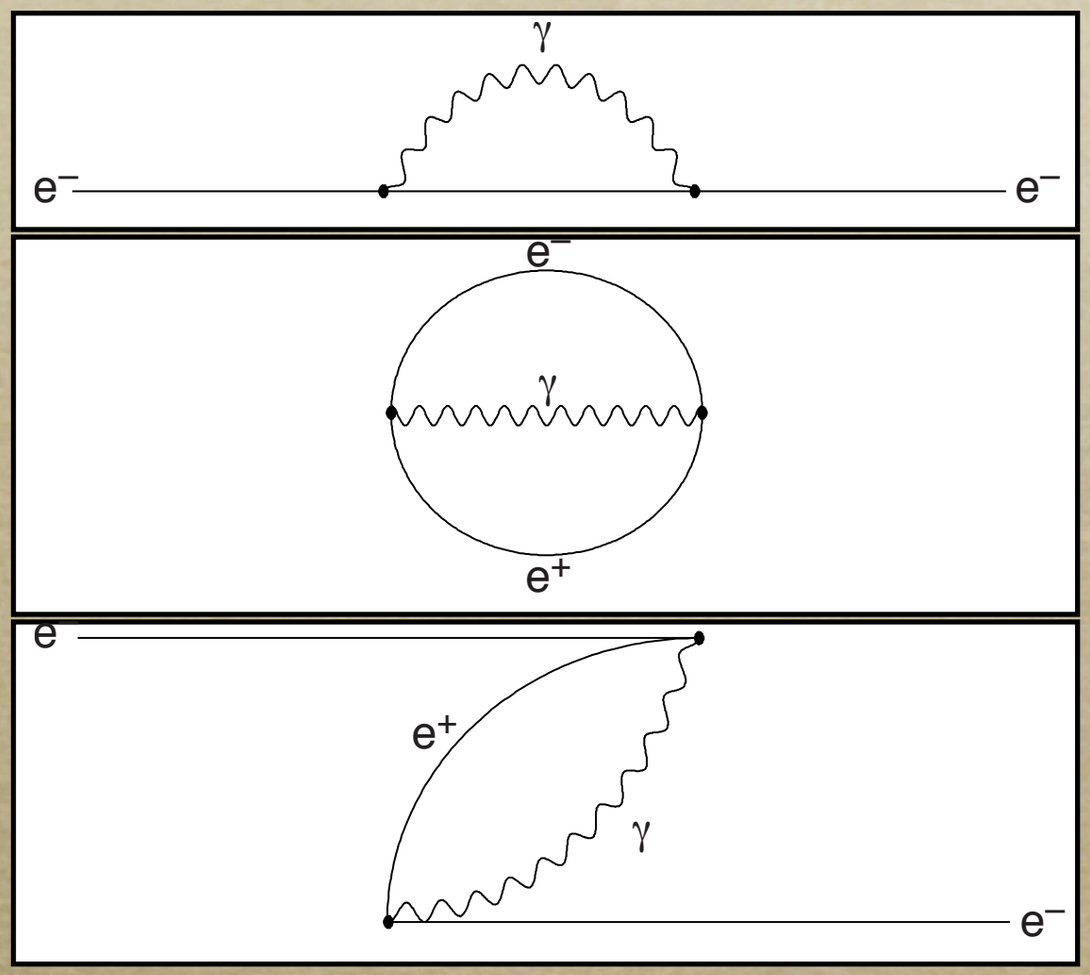

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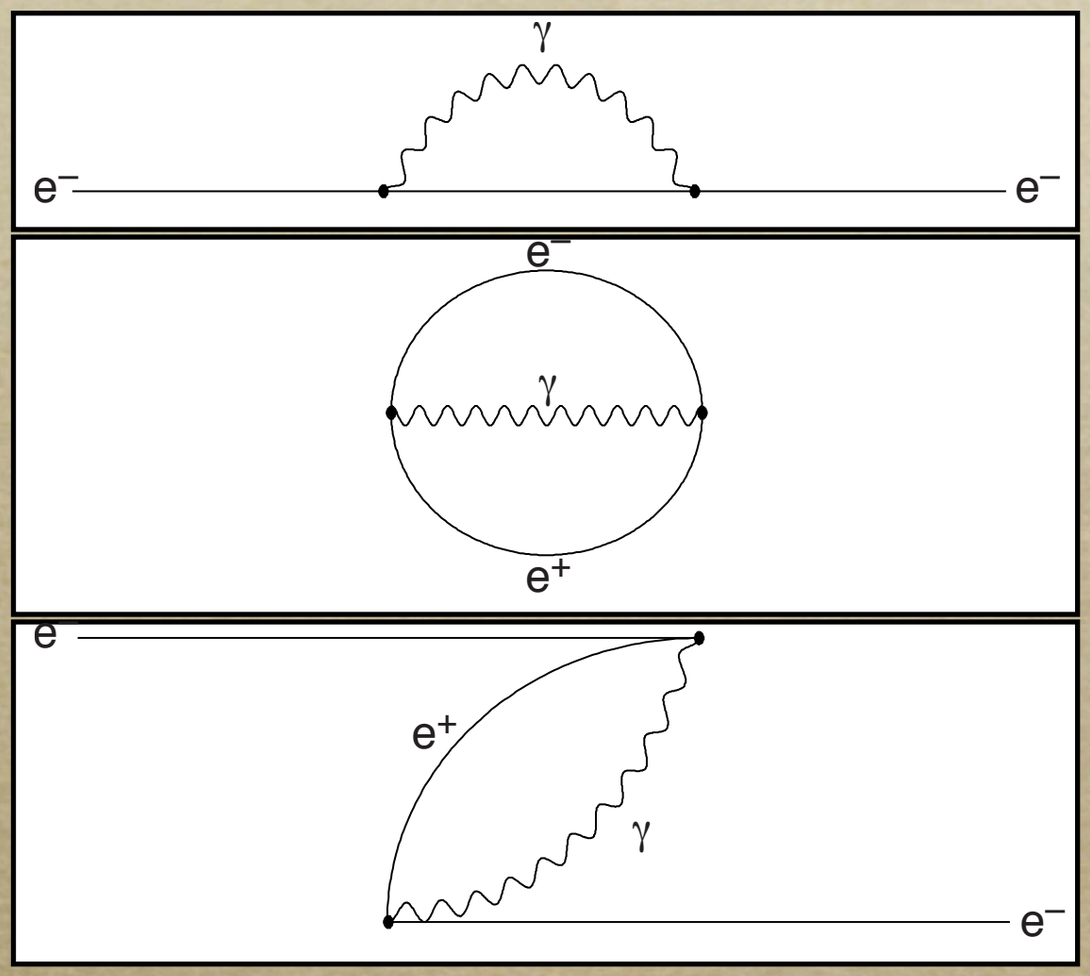
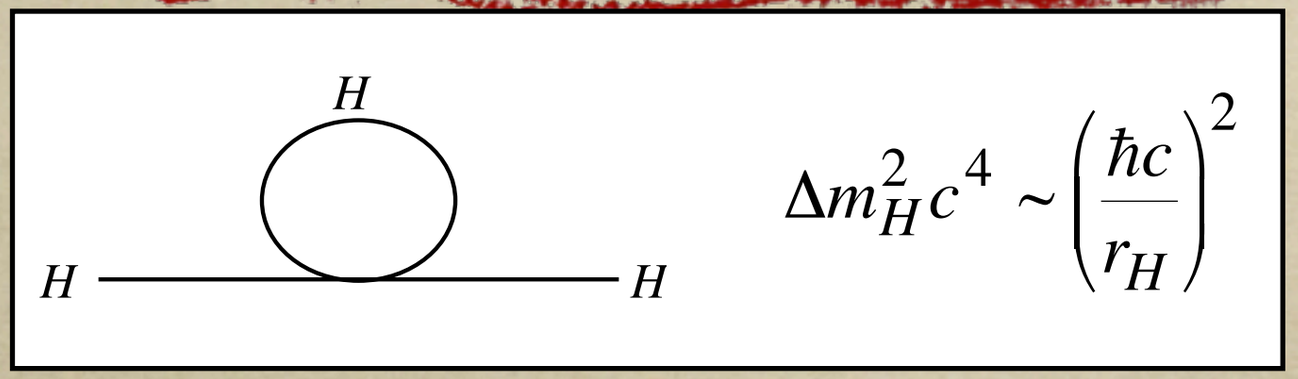
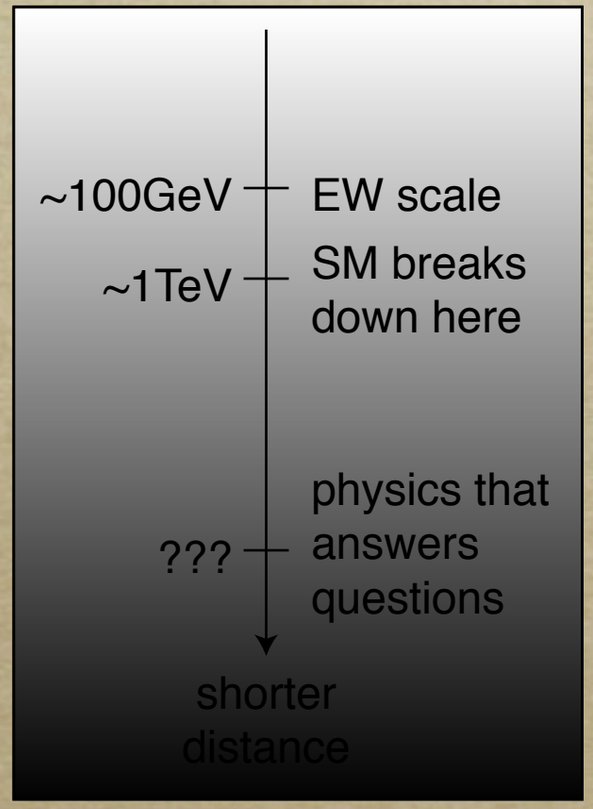


$$\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too

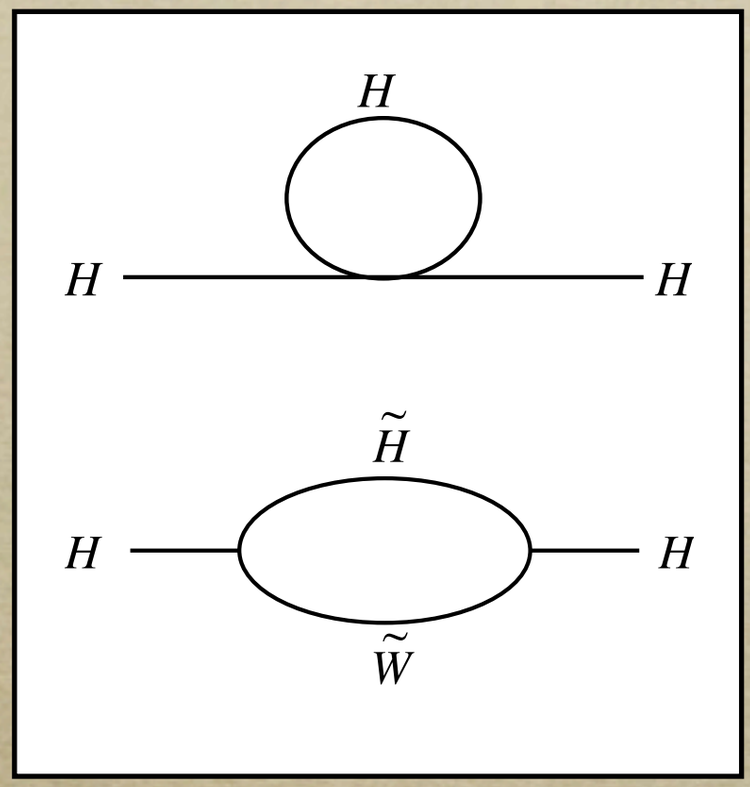
- *Just like electron repelling itself because of its charge, Higgs boson also repels itself*
- *Requires a lot of energy to contain itself in its point-like size!*
- *Breakdown of theory of weak force*
- *Can't get started!*





History repeats itself?

- *Double #particles again*
  ⇒ superpartners
- *"Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself*
- *Standard Model made consistent with whatever physics at shorter distances*



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Three Directions

- *History repeats itself*
  - *Crisis with electron solved by anti-matter*
  - *Double #particles again ⇒ supersymmetry*
- *Learn from Cooper pairs*
  - *Cooper pairs composite made of two electrons*
  - *Higgs boson may be fermion-pair composite*
    ⇒ *technicolor*
- *Physics as we know it ends at* TeV
  - *Ultimate scale of physics: quantum gravity*
  - *May have quantum gravity at* TeV
    ⇒ *hidden dimensions* (0.01 cm *to* 10^{-17} cm)


bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
MSSM + ν_R
unnified SM
axigluon
sterile ν
pseudo NGB
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lepto quark
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Weinberg's 3HD
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familon
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matrix M
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F
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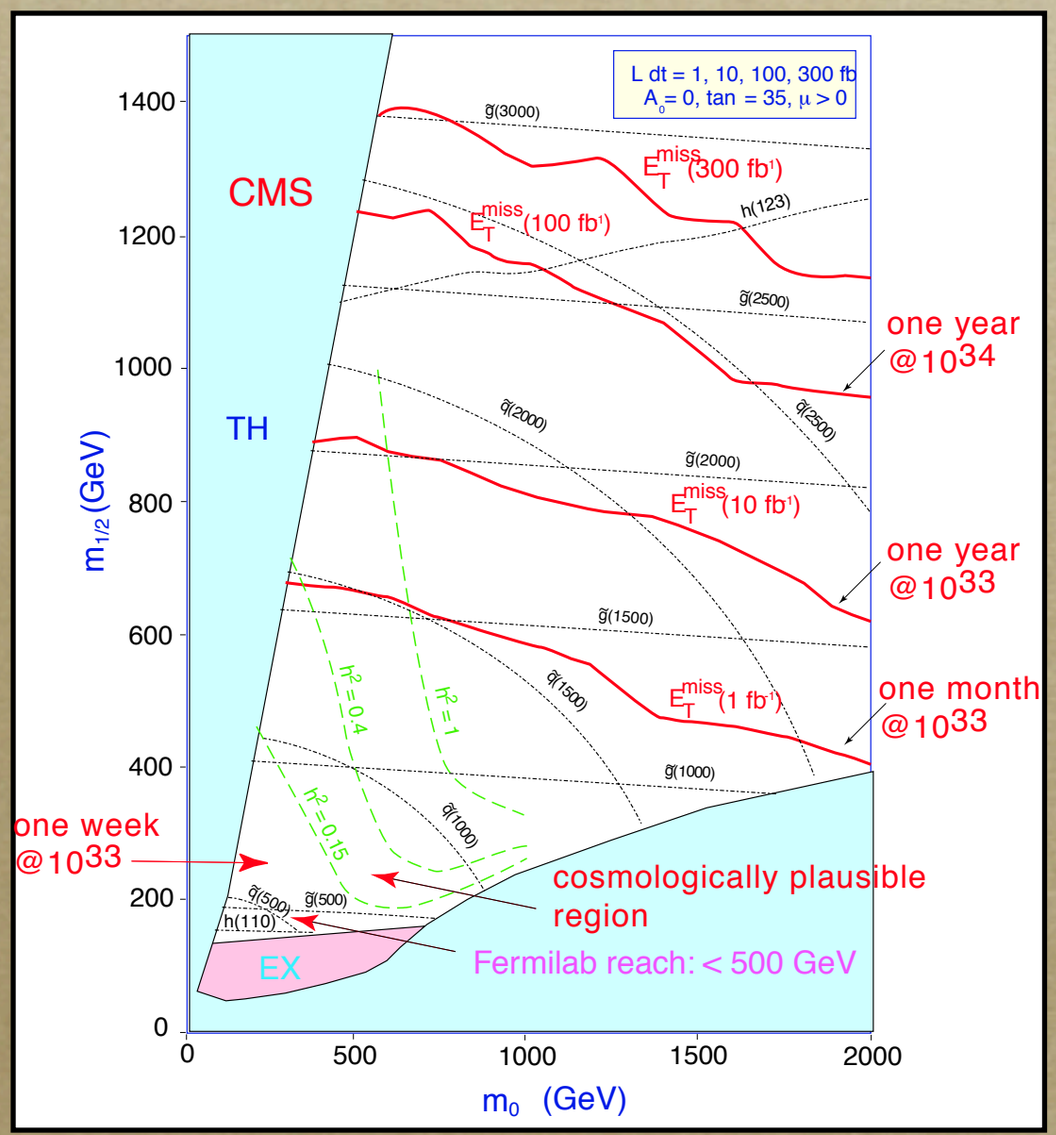
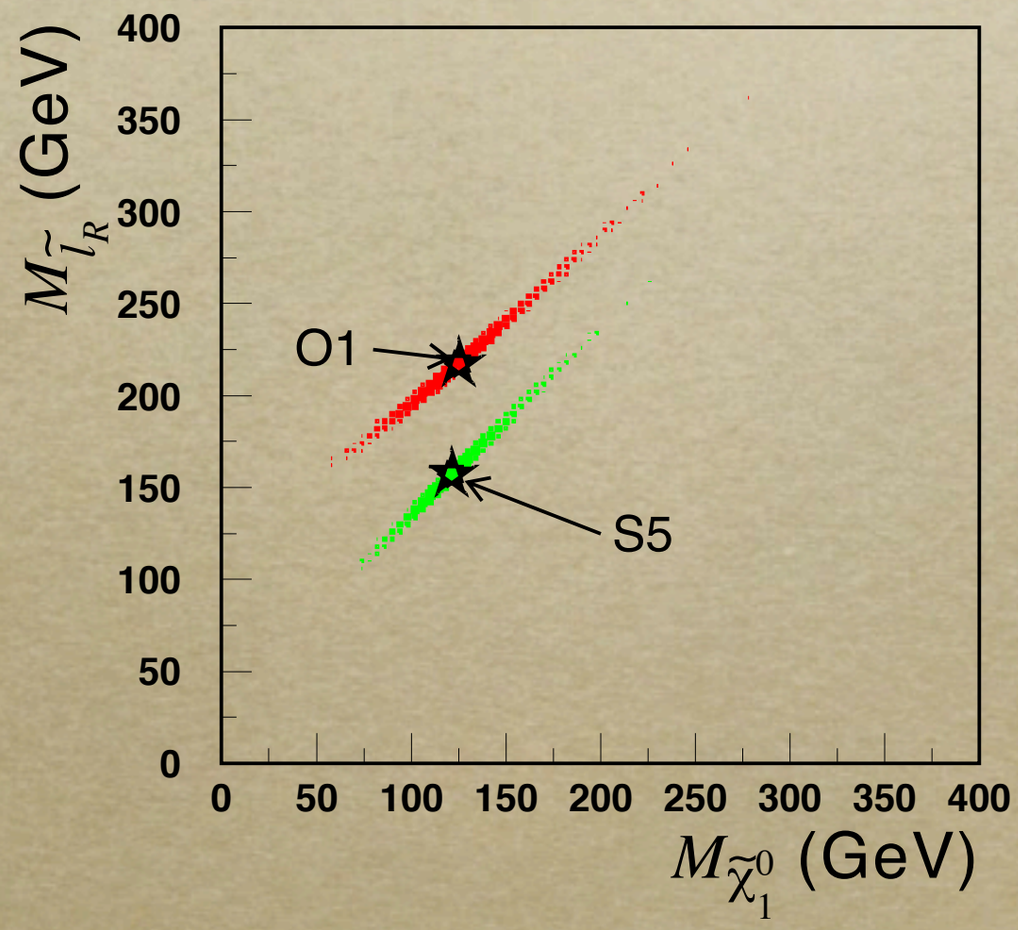
k-ssence
composite W,Z

Supersymmetry

LHC will discover supersymmetry



Can do many measurements at LHC



LHC discovery

- *case to three possible directions*
  - *look for more new physics with luminosity upgrade*
  - *study connection of new physics to flavor with B, K, mu, etc*
  - *understand properties of new particles with a lepton collider*

need precision measurements

- *SUSY spectroscopy*
- *kinematic fits, partial wave analysis, Dalitz analysis, etc*
- *precision mass, BR measurements*
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Squarks J=0? **PDG 2016**

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set A_0=0 and tanβ = 3. See Fig. 5 of the paper for other choices of A_0 and tanβ. The result is correlated with the gluino mass M_3. See listing for gluino.
[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with tanβ = 5.
[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

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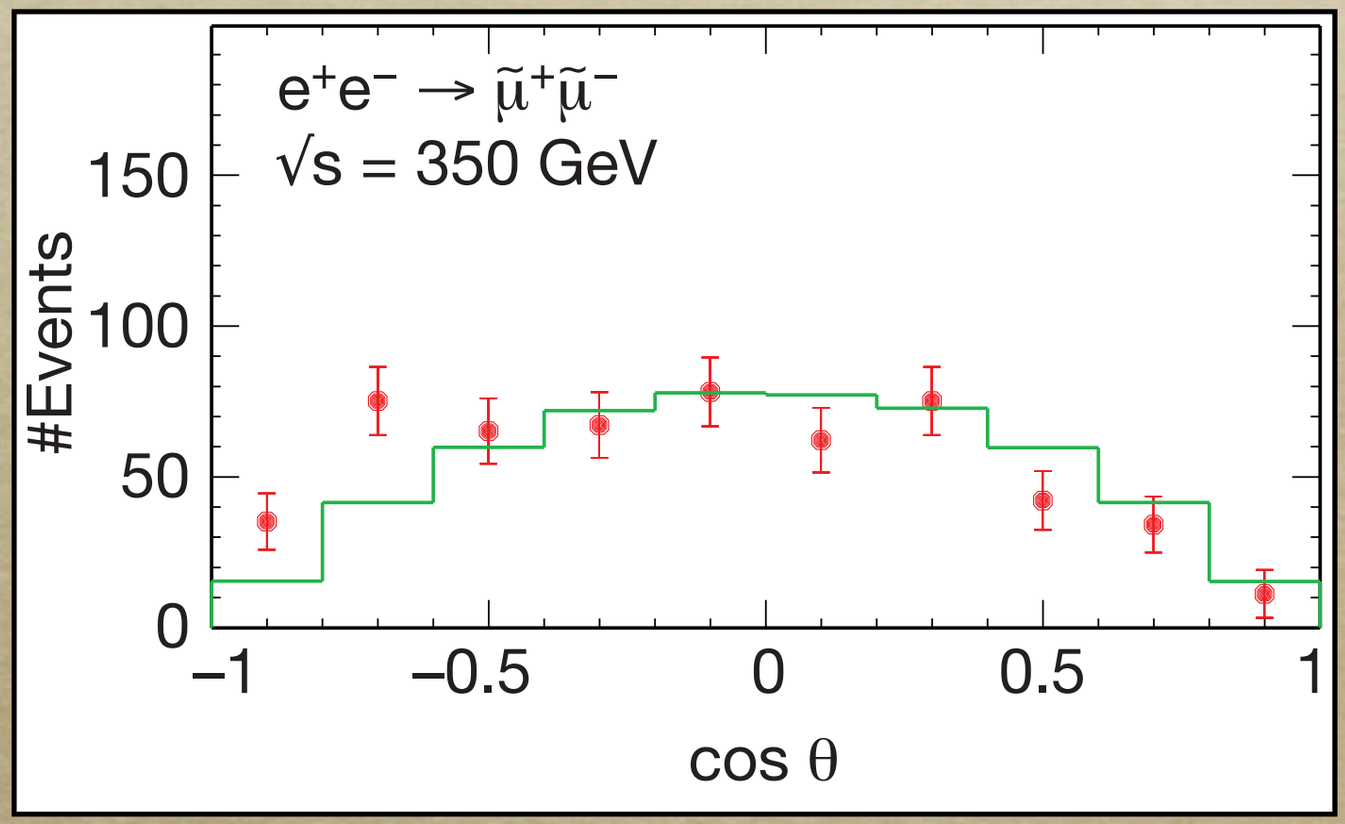
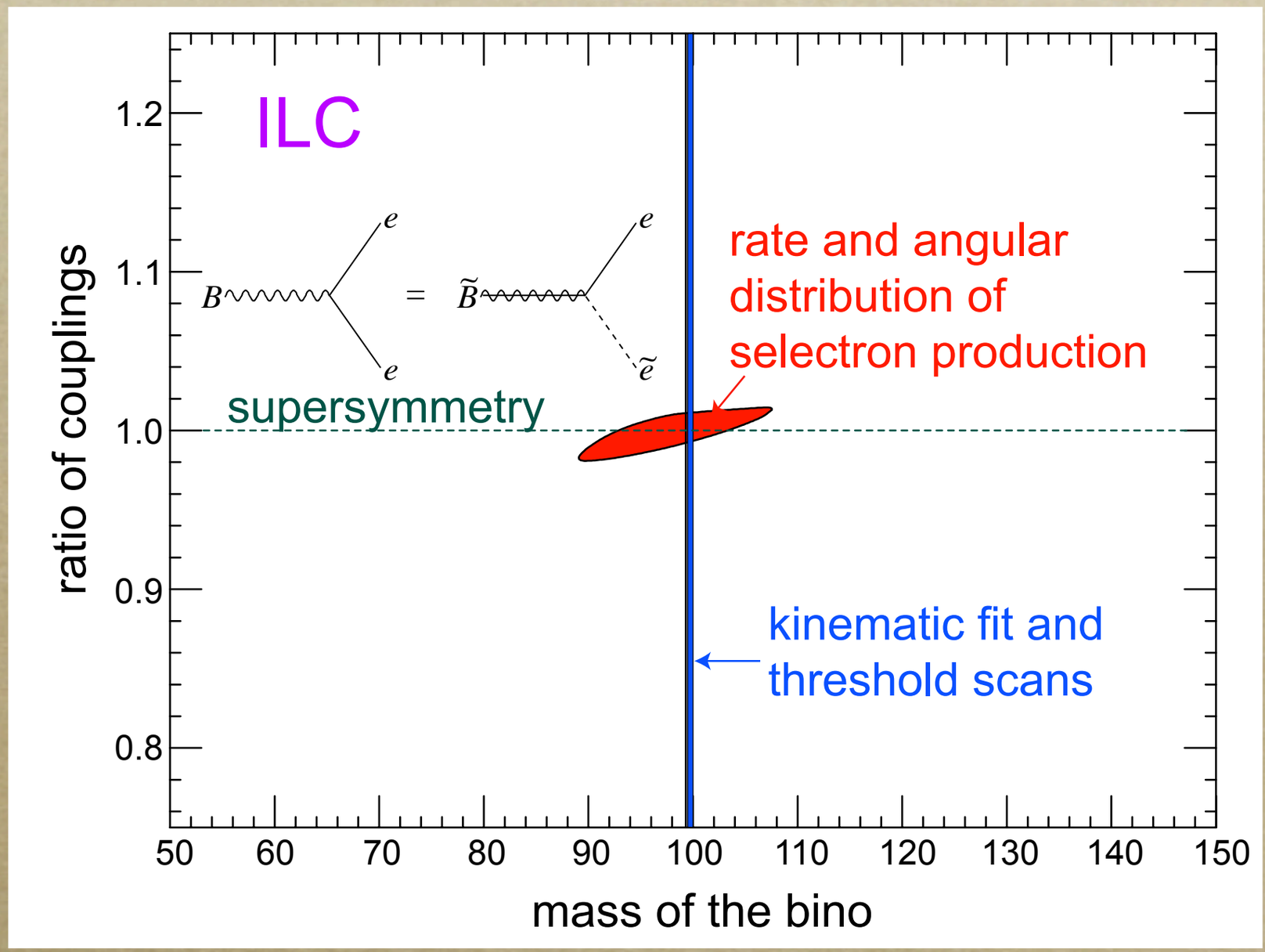
Spin 0?



Prove Supersymmetry

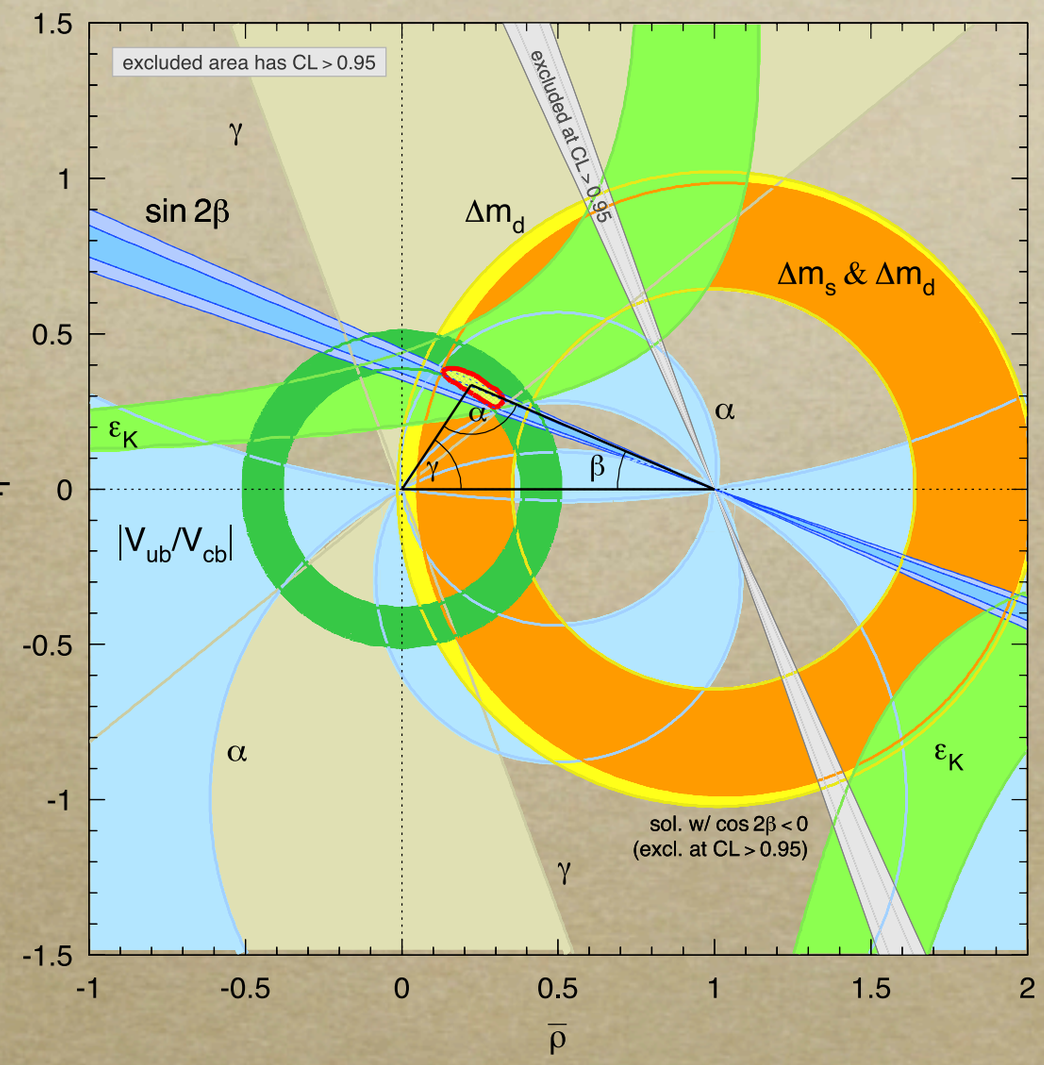
- *Test they are really superpartners @ LC*
- *Spins differ by 1/2*
- *Same gauge quantum numbers*
- *Supersymmetric couplings*



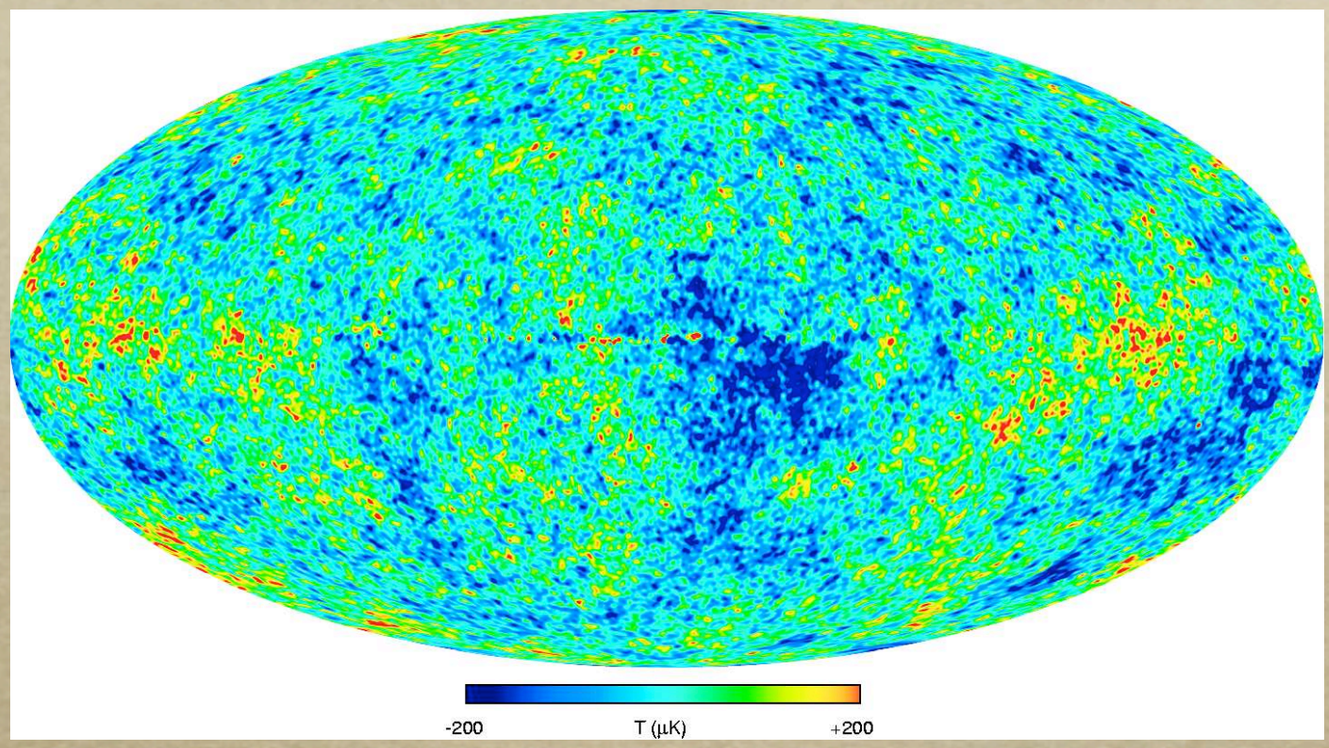
cf. imaging vs spectroscopy

Need more CP Violation

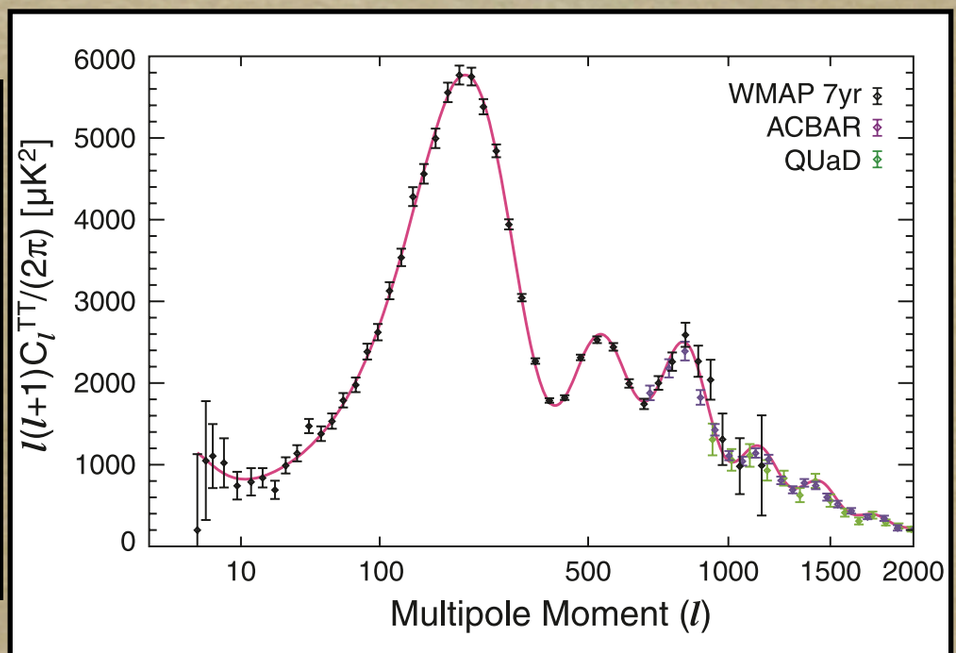
- *Belle/BaBar fantastic job to establish KM*
- *However, KM cannot produce baryon asymmetry* > 10^{-20}
- *need more sources of CP violation*
- *quarks? neutrinos?*



Cosmic Microwave Background

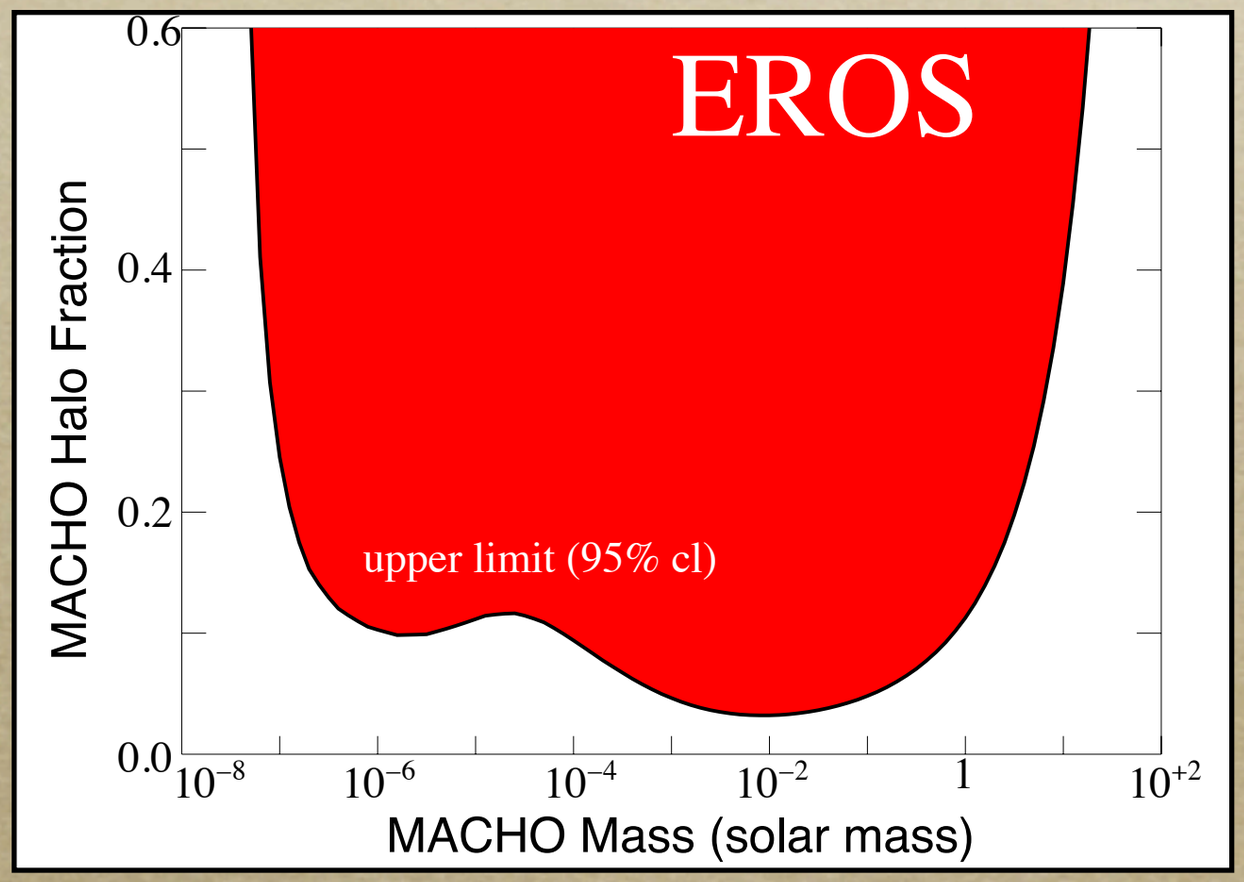


- *WMAP7 (ΛCDM)*
  - $\Omega_{CDM}h^2$=0.1109±0.0056
  - $\Omega_b h^2$=0.02258±0.00057
  - Ω_Λ=0.734±0.029
- >20σ *signal for non-baryonic dark matter*



What dark matter is not

Massive Compact Halo Object?



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- *not a dark astronomical object (MACHOs) up to* $<10^{-7} M_{Sun}$

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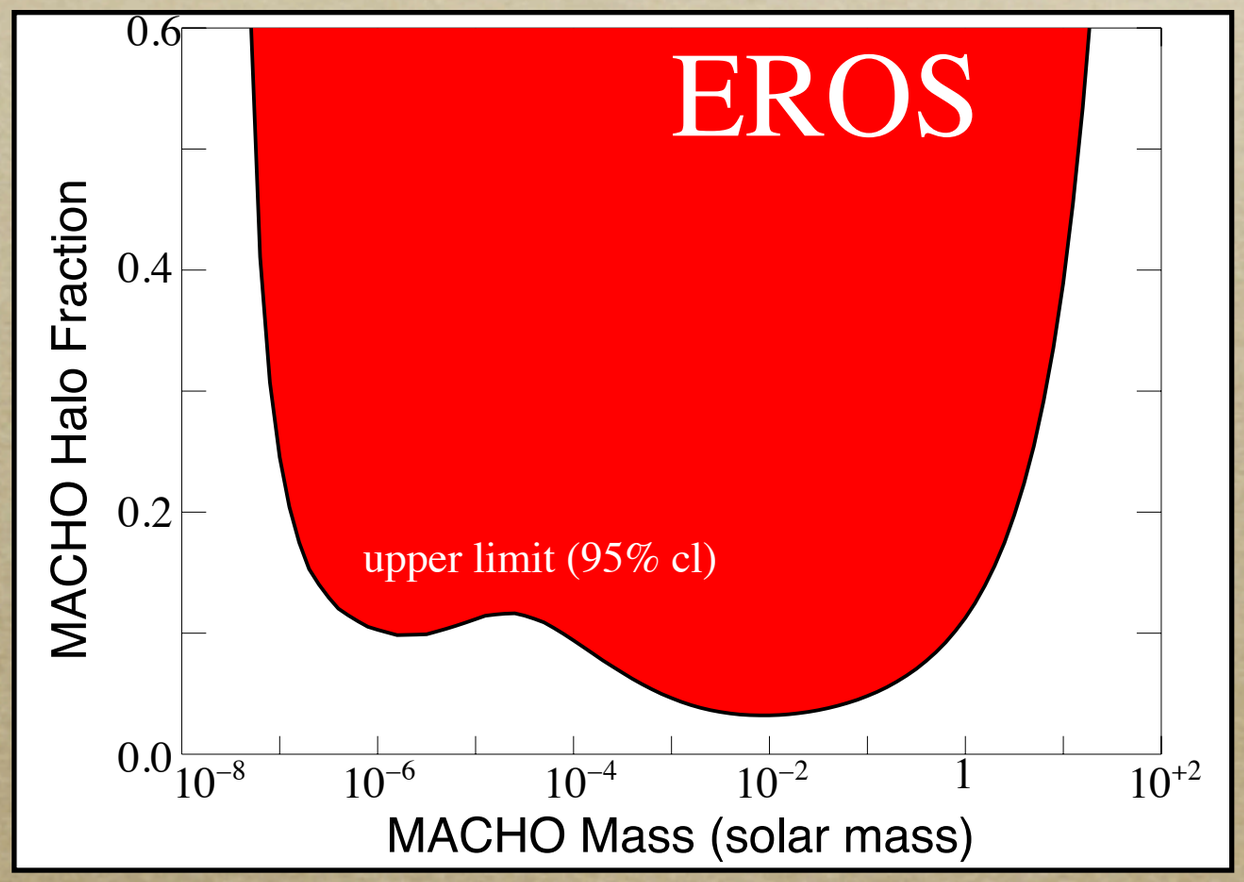

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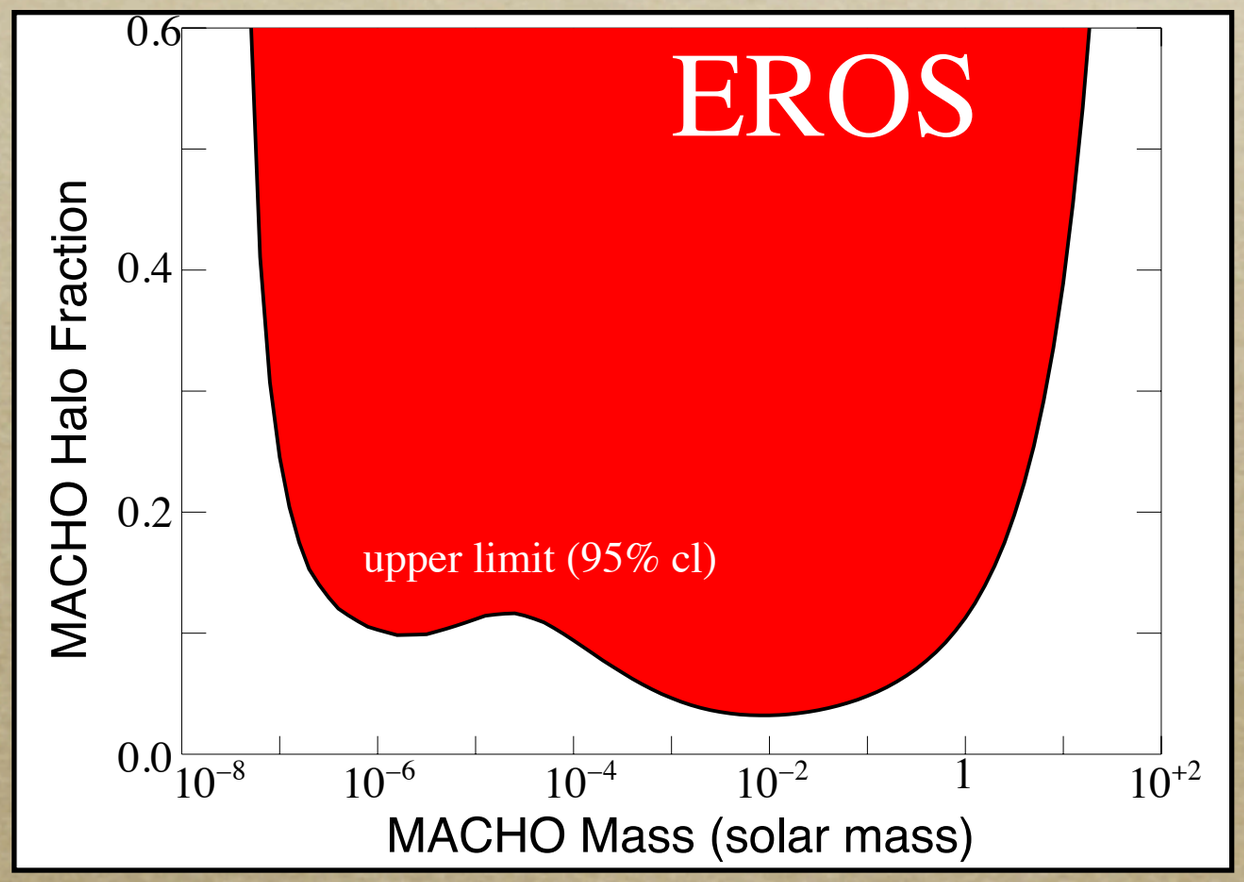

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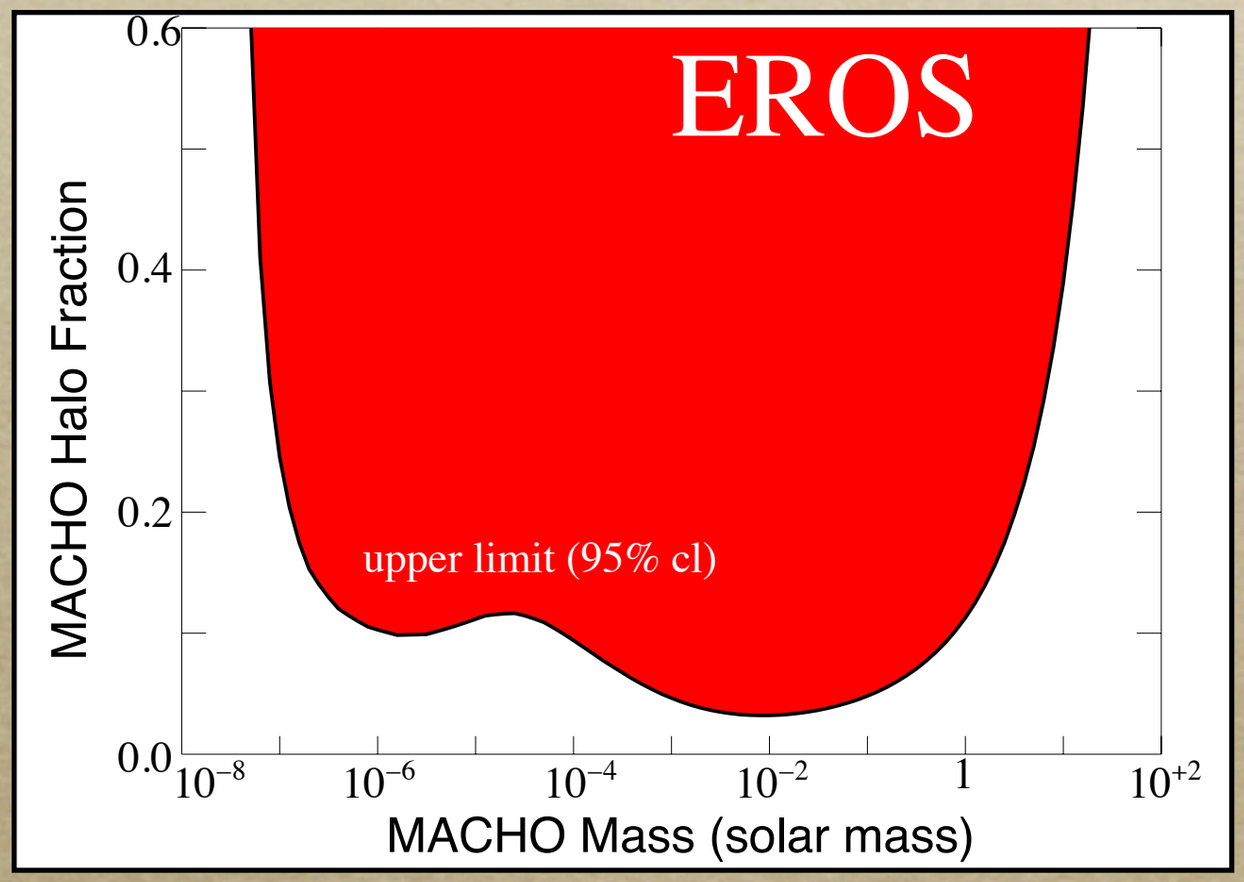

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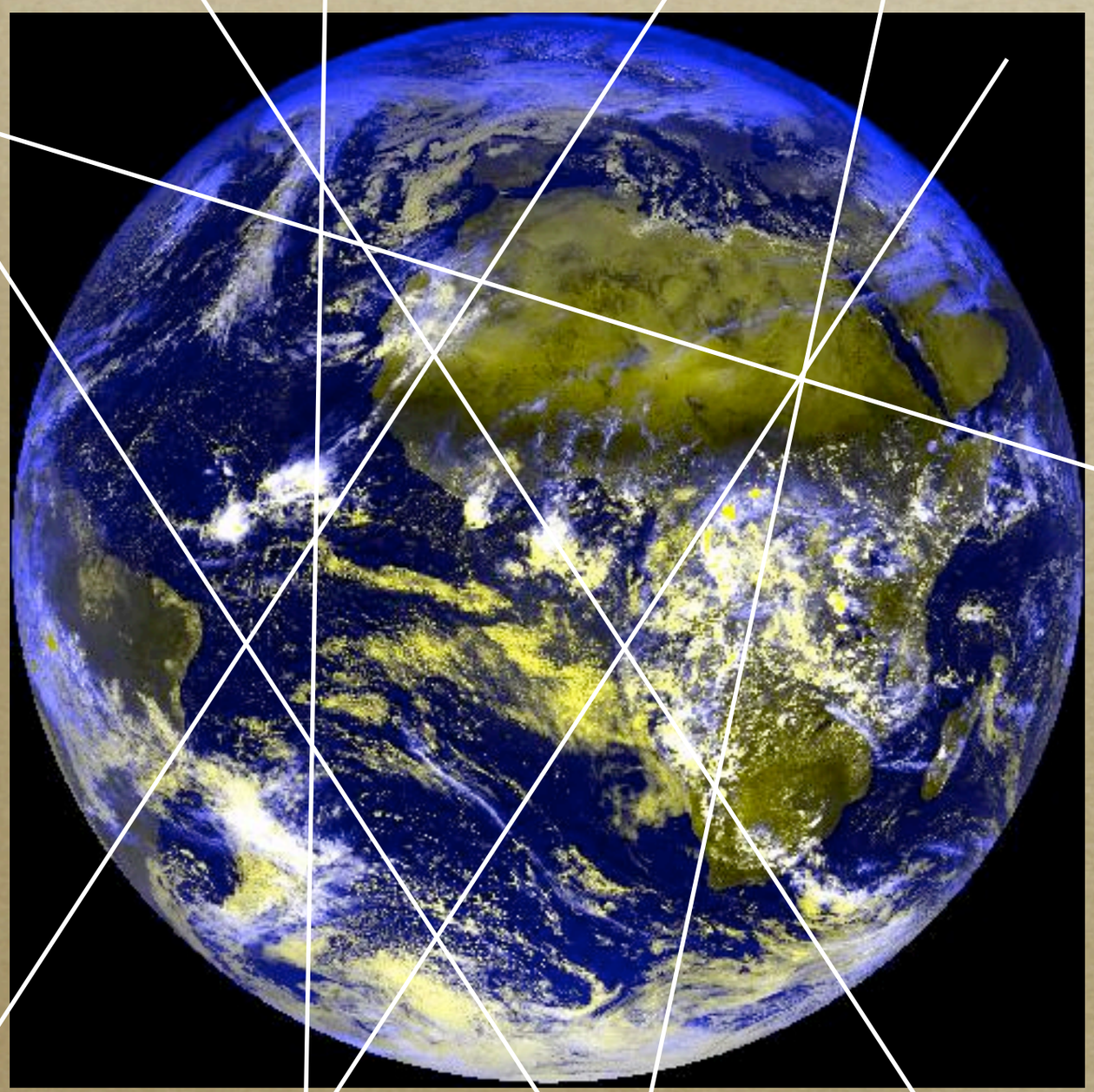
Massive Compact Halo Object?

MACHOs ⇒ WIMPs



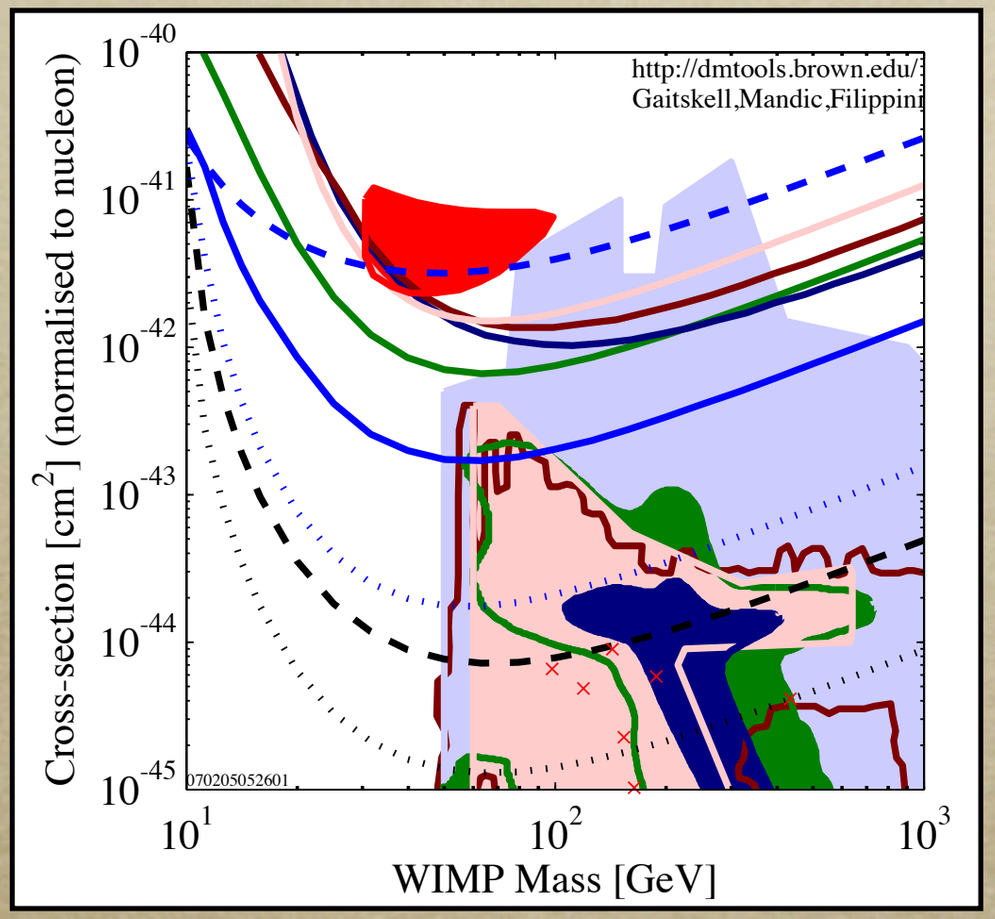
- *WIMP (Weakly Interacting Massive Particle) very attractive*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

- TeV *the correct energy scale*

Particle Dark Matter

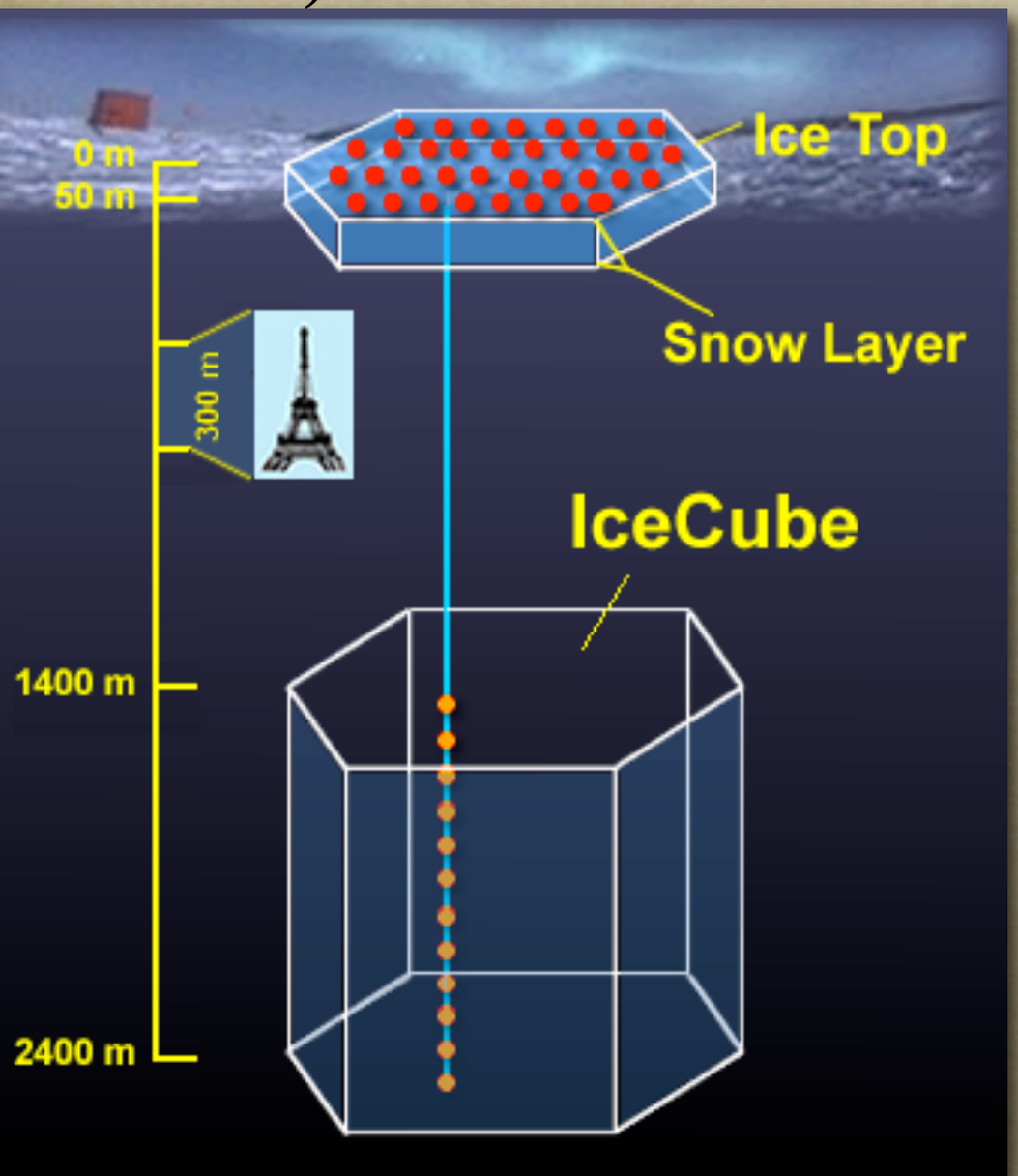
- *Stable, TeV-scale particle, electrically neutral, very weakly interacting*
- *No such candidate in the Standard Model*
- *Many models of stabilizing Higgs provide candidates*
- *LSP in SUSY, LKP in UED, LTP in little Higgs, S in NMSM, ...*

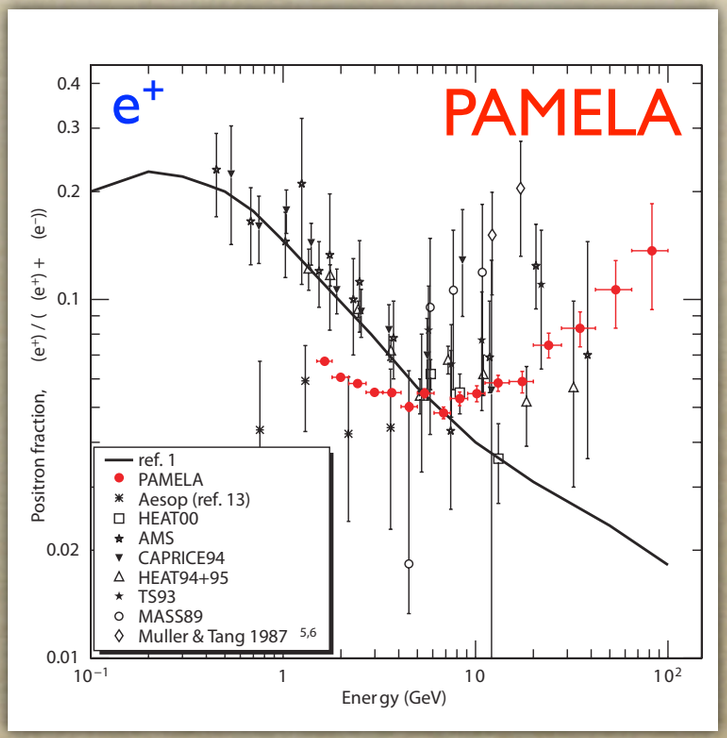


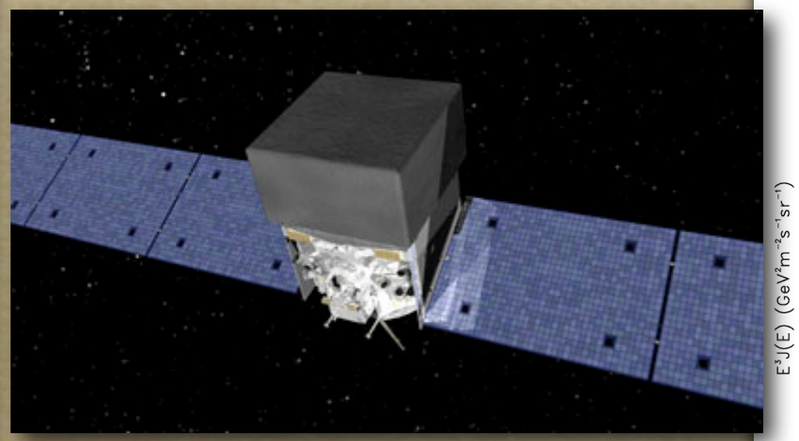
- *Detect Dark Matter to see it is there.*
- *Produce Dark Matter in accelerator experiments to see what it is.*

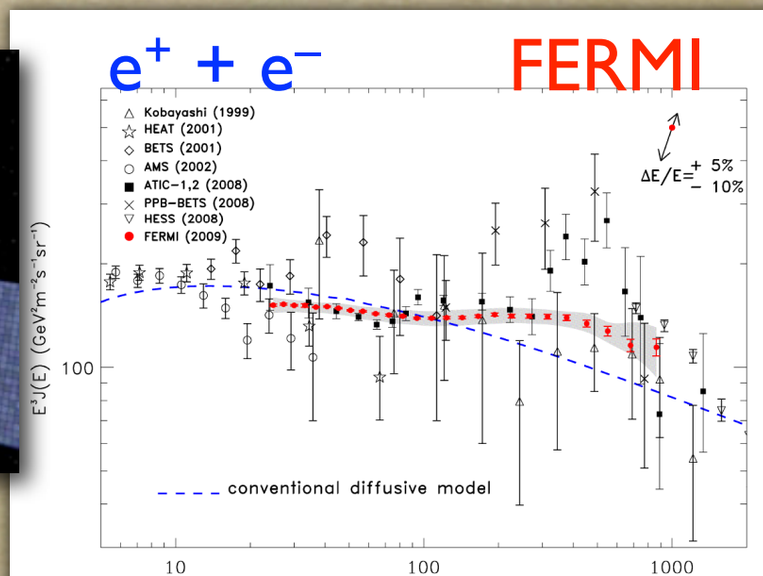
Also indirect detection

- *e^+, anti-nuclei, γ, ν*
- *halo, Gal. Center*



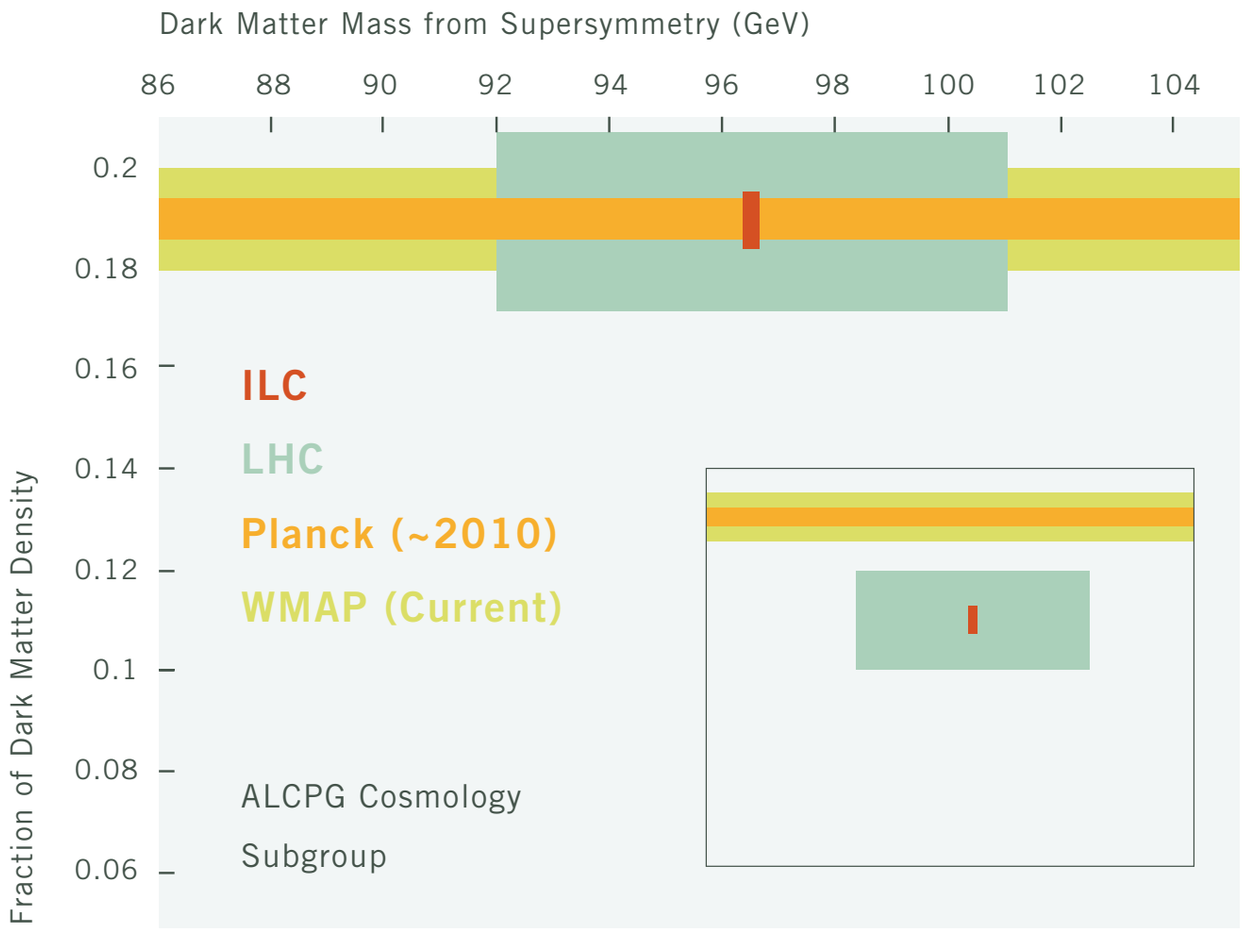






Dark Matter Concordance

abundance



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Dark Matter Concordance

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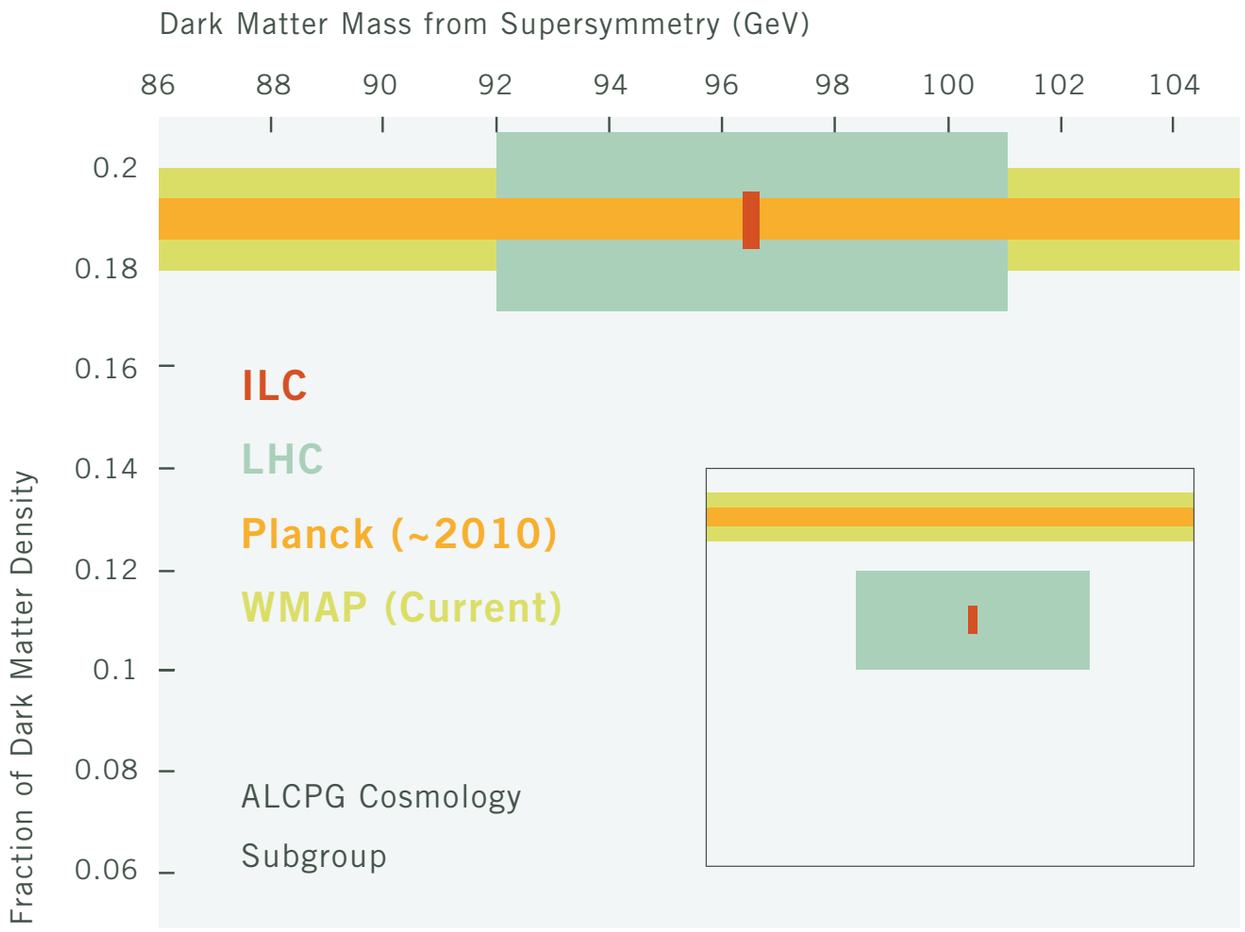
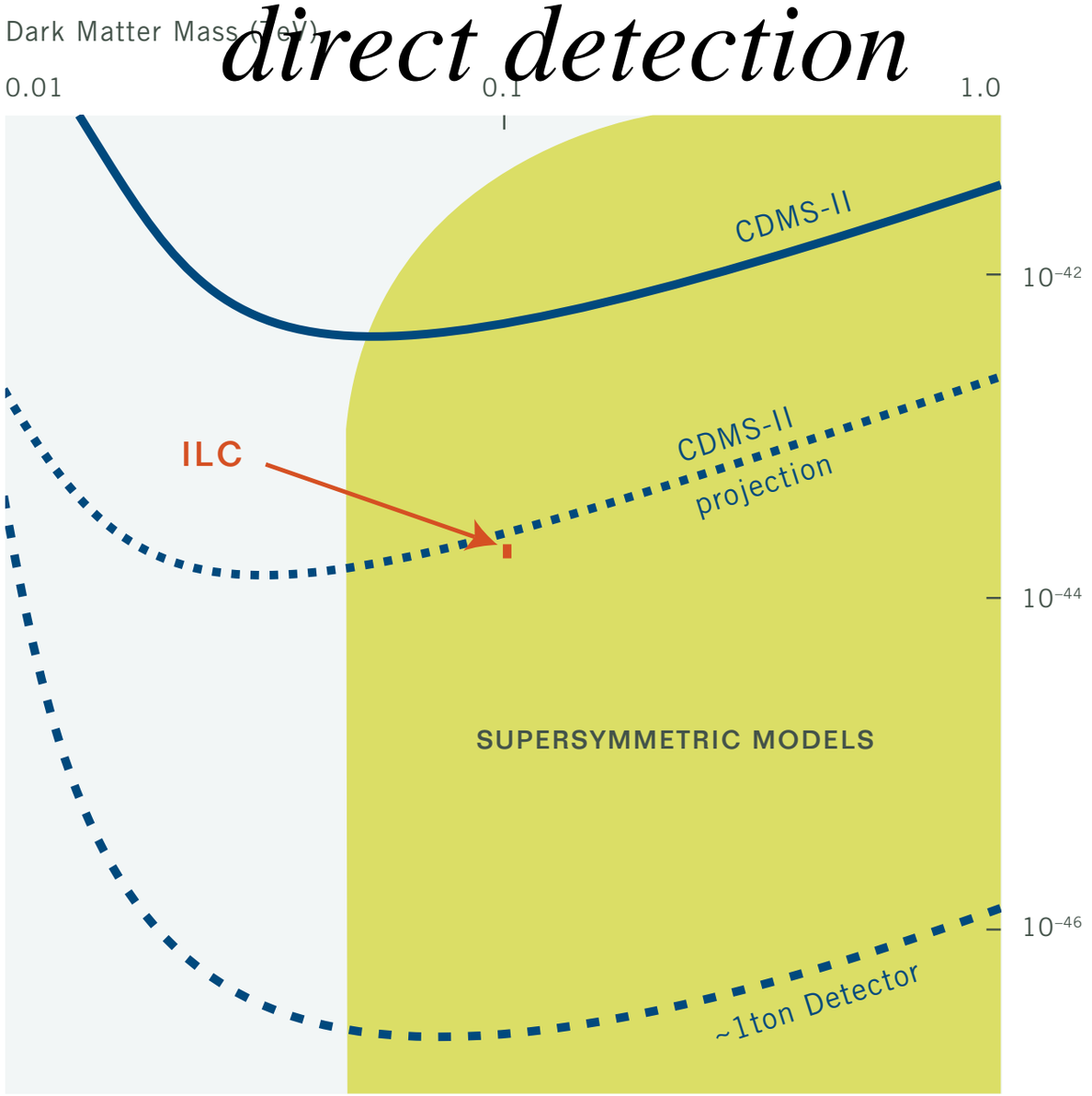
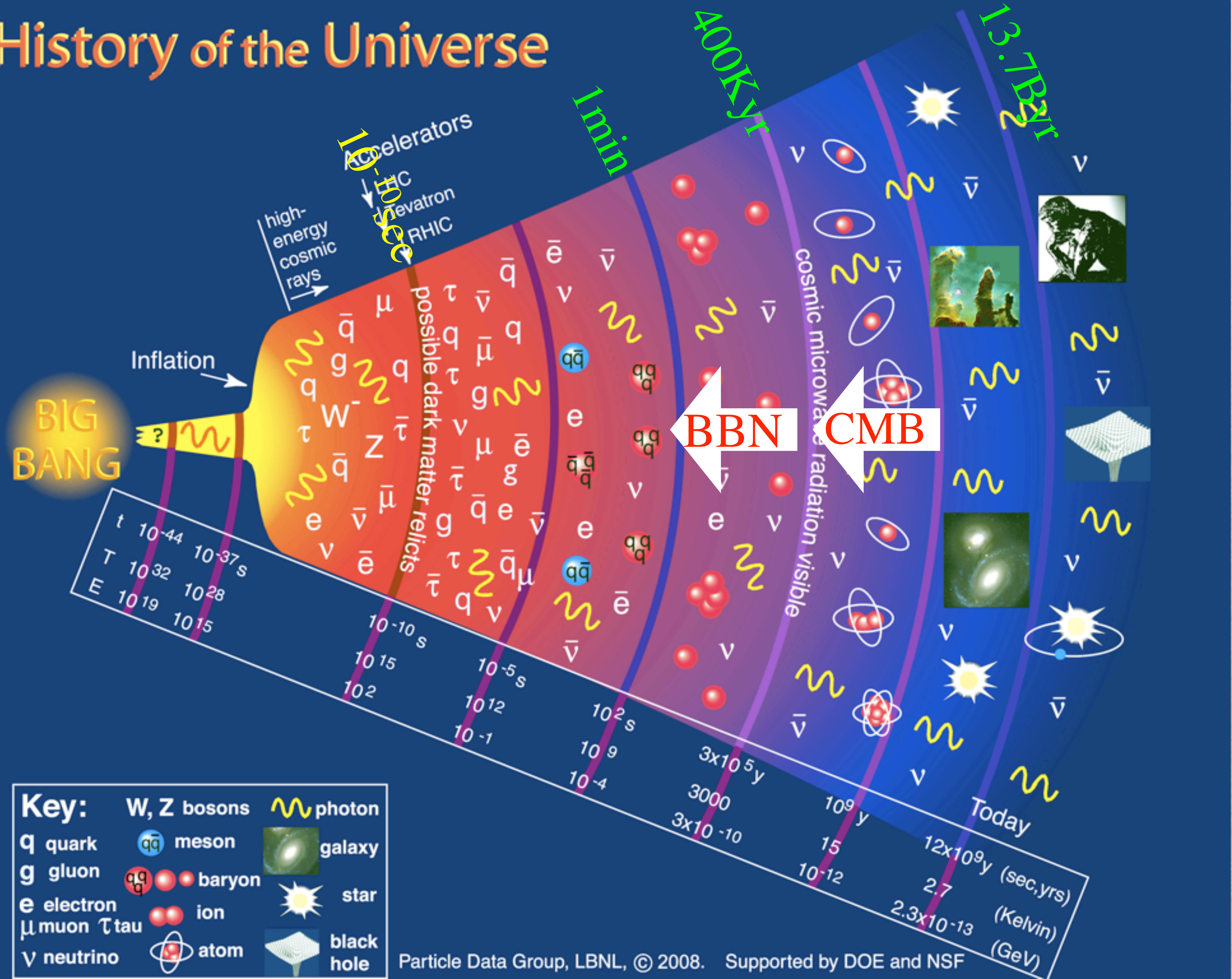


direct detection



History of the Universe



History of the Universe

BIG BANG

Inflation

high-energy cosmic rays

Accelerators
LHC
Tevatron
RHIC

10-10sec

1min

400Kyr

13.7Byr

possible dark matter relicts

cosmic microwave radiation visible

BBN

CMB

observation

Today

t	10^{-44}	10^{-37} s		10^{-10} s		10^{-5} s		10^{2} s		3×10^{5} y		10^{9} y	12×10^{9} y (sec,yrs)
T	10^{32}	10^{28}		10^{15}		10^{12}		10^{9}		3000		15	2.7 (Kelvin)
E	10^{19}	10^{15}		10^{2}		10^{-1}		10^{-4}		3×10^{-10}		10^{-12}	2.3×10^{-13} (GeV)

Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- $q\bar{q}$ meson
- qqq baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

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10 15
10 2

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10 12
10 -1

10 2 s
10 9
10 -4

3x10 5 y
3000
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US-Japan Collaboration Agreement

Benefits

- *It clearly helped young Japanese HEP scientists trained at US facilities*
- *Many important contributions to major HEP achievements*
- *also helped US participation in Japanese projects*
- *important R&D to enable future projects*

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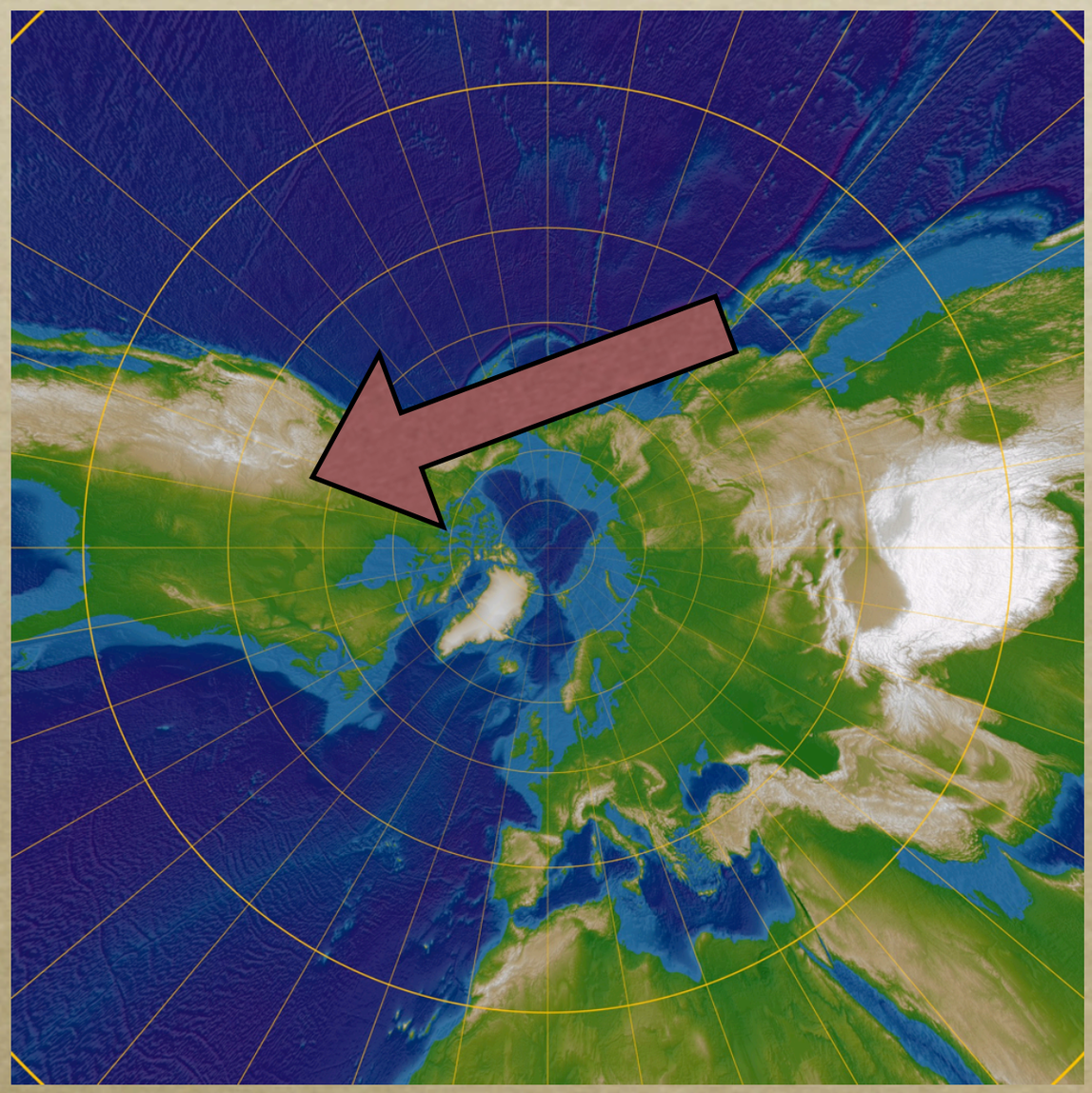
Unequal Treaty?

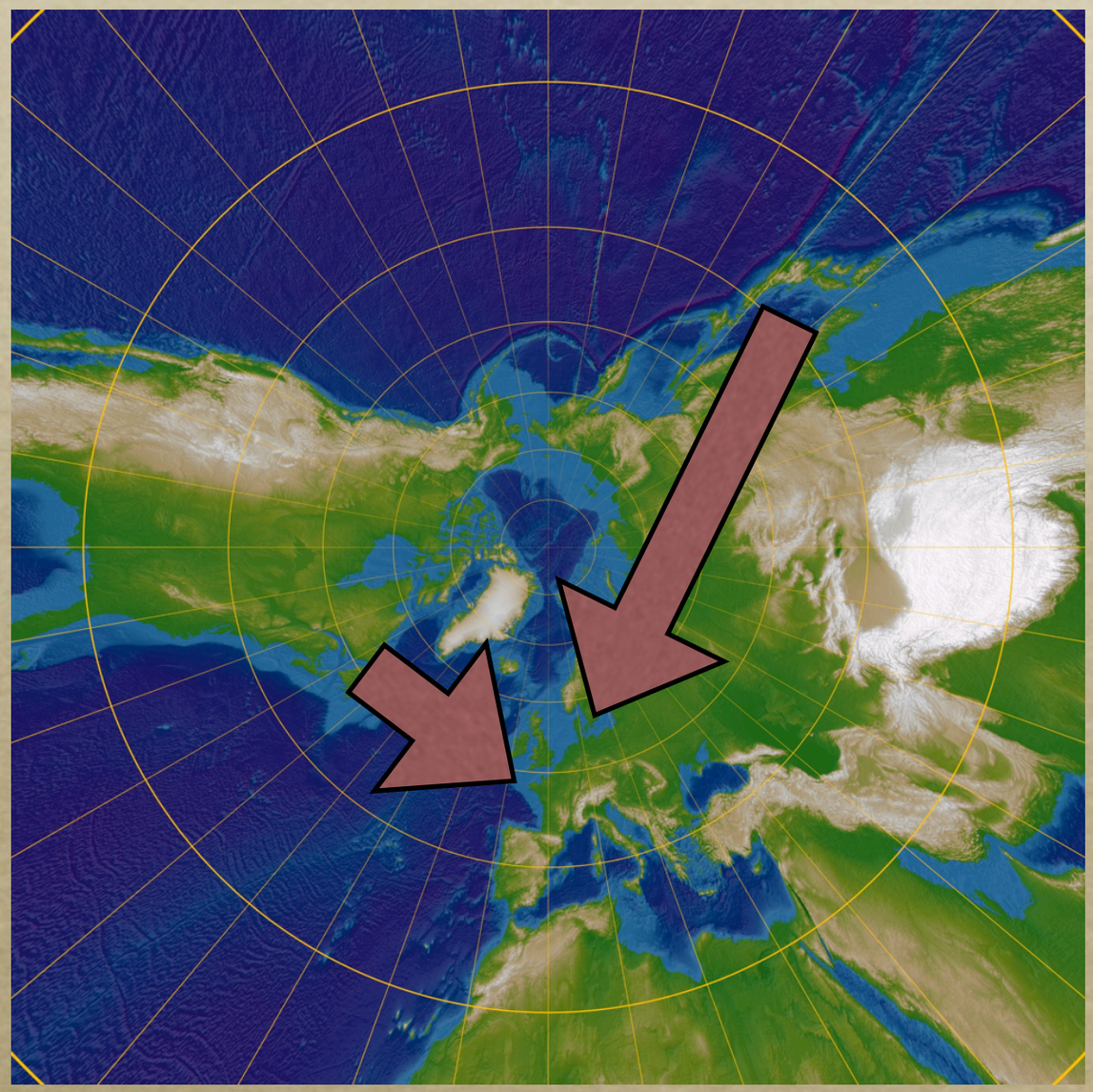
Unequal Treaty?

- *Both money and people flowed from Japan to US*
- *need to establish Japan as training grounds for young US scientists*
- *more equal partnership?*



Europe

- *With LHC, both US and Japan looking towards Europe*
- *maybe stronger case for US-Japan collaboration to avoid European monopoly?*
- *flavor physics is clearly complementary to LHC*
- *R&D for our future*



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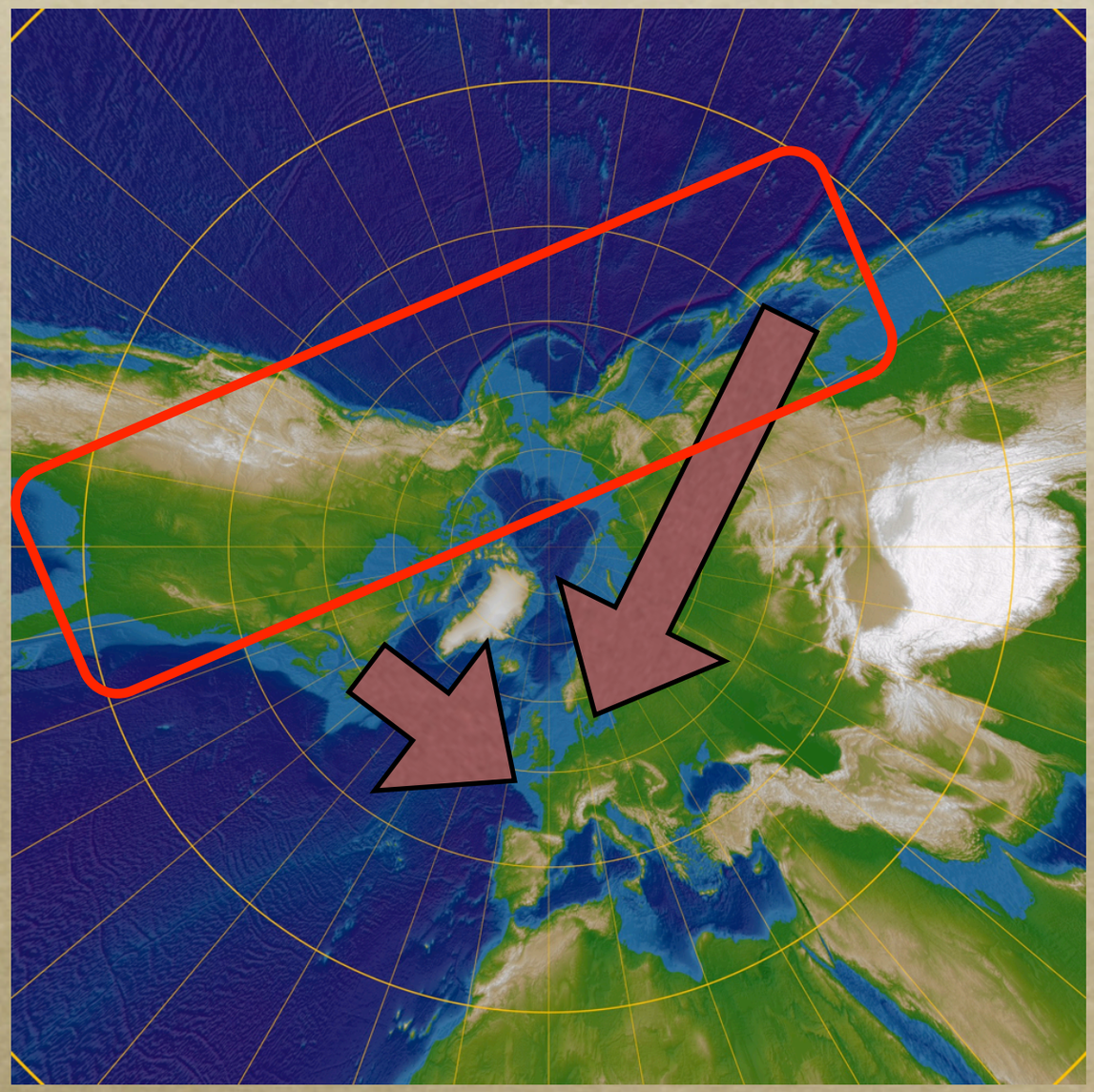

More money?

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- *Well, dark energy is supposedly an infinite source of energy*
- *Can we confuse the politicians to put more funds into HEP?*

Conclusions

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- *What is the right model?*